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9 Attorneys for Plaintiff  
Electronic Theatre Controls, Inc. d/b/a ETC

11 UNITED STATES DISTRICT COURT  
12 CENTRAL DISTRICT OF CALIFORNIA

14 ELECTRONIC THEATRE  
CONTROLS, INC. d/b/a ETC, a  
15 Wisconsin Corporation,

16 Plaintiff,

17 v.

18 ELATION LIGHTING, INC., a Nevada  
Corporation,

19 Defendant.

CASE NO.: 2:25-cv-00852

**COMPLAINT FOR PATENT  
INFRINGEMENT**

**DEMAND FOR JURY TRIAL**

1 Plaintiffs Electronic Theatre Controls, Inc. d/b/a ETC, by way of this  
2 Complaint against Defendant Elation Lighting, Inc., allege as follows:

3 **THE PARTIES**

4 1. Plaintiff Electronic Theatre Controls, Inc. d/b/a ETC (“ETC”) is a  
5 Wisconsin corporation, with its principal place of business located at 3031 Pleasant  
6 View Road, Middleton, WI 53562.

7 2. ETC is a leading supplier of lighting products and control systems for  
8 theatrical applications.

9 3. On information and belief, Defendant Elation Lighting, Inc.  
10 (“Elation”) is a Nevada corporation having a principal place of business at 6122 S.  
11 Eastern Avenue, Los Angeles, California.

12 **JURISDICTION AND VENUE**

13 4. This is a civil action for patent infringement arising under the patent  
14 laws of the United States, 35 U.S.C. § 1 *et. seq.*, including 35 U.S.C. § 271, arising  
15 from Elation’s actions, including making, using, selling, offering for sale and/or  
16 importing into the United States one or more products that infringe U.S. Patent Nos.  
17 8,593,074 (“the ‘074 patent”), 11,240,898 (“the ‘898 patent”), and 11,849,519 (“the  
18 ‘519 patent”), including, without limitation, the Fuze Teatro light fixture (the  
19 “Accused Products”). This Court has subject matter jurisdiction under 28 U.S.C. §§  
20 1331 and 1338(a).

21 5. This Court has personal jurisdiction over Defendant because Defendant  
22 engages in business within this district, including having its principal place of  
23 business in this district, and has made, used, offered to sell and sold the Accused  
24 Products in this District.

25 6. Venue is proper in this district under 28 U.S.C. § 1400(b) because the  
26 Defendant has regular and established place of business in this district and has  
27 committed acts of infringement in this district.

**BACKGROUND**

7. ETC is the sole owner of the ‘074 patent, the ‘898 patent, and the ‘519 patent (collectively, the “ETC Patents”).

8. The ‘074 patent is titled “Systems and methods for controlling an output of a light fixture” was duly and legally issued by the United States Patent and Trademark Office on November 26, 2013. A true and complete copy of the ‘074 patent is attached hereto as Exhibit A. The ‘074 patent is valid and enforceable.

9. The ‘898 patent is titled “Systems, methods, and devices for influencing spectral content of a light output” and was duly and legally issued by the United States Patent and Trademark Office on February 1, 2022. A true and complete copy of the ‘898 patent is attached hereto as Exhibit B. The ‘898 patent is valid and enforceable.

10. The ‘519 patent is titled “Systems, methods, and devices for influencing spectral content of a light output” was duly and legally issued by the United States Patent and Trademark Office on December 19, 2023. A true and complete copy of the ‘519 patent is attached hereto as Exhibit C. The ‘519 patent is valid and enforceable.

11. As the owner of the ETC Patents, ETC is authorized and has standing to bring legal action to enforce all rights arising from the ETC Patents.

12. Plaintiff notified Defendant of its infringement of the ETC Patents on November 20, 2024.

13. Defendant has had constructive knowledge of infringement at least by virtue of ETC complying with 35 U.S.C. §287 by marking substantially all associated patented products with the website at [www.etcconnect.com/IP/](http://www.etcconnect.com/IP/), which lists those products as being covered by the ETC Patents.

14. Defendant has had actual knowledge of the ETC patents and infringement of that no later than November 20, 2024.

**COUNT I**

**Patent Infringement of the '074 patent**

15. ETC realleges and incorporates the foregoing paragraphs as though fully set forth herein.

16. ETC has the right to enforce the '074 patent and right to recover damages for infringement.

17. Elation has directly infringed one or more claims of the '074 patent by making, using, offering to sell and/or importing the Accused Products.

18. With knowledge of the '074 patent, Elation has induced infringement of one or more claims of the '074 patent by actively encouraging others to make, use, offer to sell, sell and/or import the Accused Products knowing that such encouragement would result in direct infringement by others.

19. With knowledge of the '074 patent, Elation has contributed to infringement of one or more claims of the '074 patent by providing the Accused Products to others knowing that the Accused Products are a material part of the invention and especially made for use in a manner that infringes the '074 patent, and not a staple article or commodity of commerce suitable for substantial noninfringing use.

20. By way of example, the Accused Products infringe claim 14 of the '074 patent.

21. Claim 14 of the '074 patent states:

14. A system for controlling the output of a light fixture, the system including:

four or more light sources; and  
a controller configured to

receive a first input parameter corresponding  
to a first color point within a color space,

1 receive a second input parameter associated  
2 with a desired intensity for the first color point,

3 determine a white point based on a  
4 relationship between the second input parameter  
5 and the color temperature of a black-body radiator,  
6 the white point corresponding to a second color  
point within the color space,

7 select a color temperature transform based  
8 on the white point,

9 calculate a third color point within the color  
10 space based on the color temperature transform,  
11 the color temperature transform defining a  
12 relationship between the first color point and the  
13 third color point, the third color point being  
14 different than the first color point, and the third  
color point being different than the second color  
point,

15 determine a respective light source output  
16 value for each of the four or more light sources  
17 based on the third color point, and

18 drive each of the four or more light sources  
19 at the respective light source output value to  
20 produce the output of the light fixture.

21 22. The Accused Products include all limitations of claim 14 of the '074  
22 patent.

23 23. The Accused Products are a system for controlling the output of a  
24 light fixture.

25 24. The Accused Products include four or more light sources.  
26 Specifically, the Accused Products have at least red, green blue, mint and amber  
27 LED light sources.

28 25. The Accused Product includes a controller.

1           26. The controller of Accused Products is configured to receive a first  
2 input parameter corresponding to a first color point within a color space. For  
3 example, Accused Products are configured to receive a DMX value corresponding  
4 to a selected color point within a color space.

5           27. The controller of Accused Products is configured to receive a second  
6 input parameter associated with a desired intensity for the first color point by  
7 receiving a DMX value corresponding to a selected intensity for the first color  
8 point.

9           28. On information and belief, the controller of Accused Products is  
10 configured determine a white point based on a relationship between the second  
11 input parameter and the color temperature of a black-body radiator, the white point  
12 corresponding to a second color point within the color space.

13           29. On information and belief, the controller of Accused Products is  
14 configured to select a color temperature transform based on the white point as the  
15 intensity of the first color point is changed during dim-to-warm control.

16           30. On information and belief, the controller of Accused Products is  
17 configured to calculate a third color point within the color space based on the color  
18 temperature transform, the color temperature transform defining a relationship  
19 between the first color point and the third color point, the third color point being  
20 different than the first color point, and the third color point being different than the  
21 second color point.

22           31. On information and belief, the controller of Accused Products is  
23 configured to determine a respective light source output value for each of the four  
24 or more light sources based on the third color point.

25           32. On information and belief, the controller of Accused Products is  
26 configured to drive each of the four or more light sources at the respective light  
27 source output value to produce the output of the light fixture.

28

33. Elation knew that making, using, offering to sell, selling, and/or importing the Accused Products and instructing others to use the Accused Products in an infringing manner would infringe the '074 patent and that use of the Accused Products would contribute to direct infringement by another. Elation's past and continued infringement of the '074 patent has been and continues to be willful and deliberate.

34. Because of Elation's infringement of the '074 patent, ETC has suffered and will continue to suffer irreparable harm and monetary damages, which continue to accrue, in an amount to be determined at trial.

35. Elation's willful infringement will continue unless enjoined by this Court.

## COUNT II

## Patent Infringement of the '898 patent

36. ETC realleges and incorporates the foregoing paragraphs as though fully set forth herein.

37. ETC has the right to enforce the '898 patent and right to recover damages for infringement.

38. Elation has directly infringed one or more claims of the '898 patent by making, using, offering to sell and/or importing the Accused Products.

39. With knowledge of the '898 patent, Elation has induced infringement of one or more claims of the '898 patent by actively encouraging others to make, use, offer to sell, sell and/or import the Accused Products knowing that such encouragement would result in direct infringement by others.

40. With knowledge of the '898 patent, Elation has contributed to infringement of one or more claims of the '898 patent by providing the Accused Products to others knowing that the Accused Products are a material part of the invention and especially made for use in a manner that infringes the '898 patent.

1 and not a staple article or commodity of commerce suitable for substantial  
2 noninfringing use.

3 41. By way of example, Elation's and others use of the Accused Products  
4 infringes claim 1 of the '898 patent.

5 42. Claim 1 of the '898 patent states:

6 1. A method for control of a light fixture, the  
7 method comprising:

8 energizing the light fixture to produce a first light  
9 output with a first chromaticity and a first spectral power  
10 distribution;

11 receiving a user input representative of a desired  
12 adjustment of a lighting effect;

13 generating a target spectrum based on the user  
14 input; and

15 energizing the light fixture to produce a second  
16 light output with the first chromaticity and a second  
17 spectral power distribution, the second power distribution  
approximates the target spectrum.

18 43. The Accused Products provide a method for control of light fixture.  
19 The Accused Products are a light fixture that is controlled by a user.

20 44. When used, the Accused products are energized to produce a first  
21 light output with a first chromaticity and a first spectral power distribution. For  
22 example, a user of the Accused Products can send a specific DMX value to a  
23 specific channel to select a correlated color temperature at a default (brightest)  
24 output.

25 45. The Accused Products receive a user input that represents a desired  
26 adjustment of a lighting effect (e.g., light quality). For example, from the brightest  
27 output setting, the Accused Products can receive a DMX value to select a balanced  
28 or a fidelity output setting.



1           46. The Accused Products generate a target spectrum based on the user  
2 input. For example, Elation touts that the Accused Products “allow[] user to select  
3 between Highest Output, Highest Fidelity, or a blend of both,” that selection results  
4 in the generation of the target spectrum.

5           47. The Accused Products are further energized to produce a second light  
6 output with the first chromaticity and a second spectral power distribution, the  
7 second power distribution approximates the target spectrum. For example, when  
8 starting with the default brightest output, a user of the Accused Products may  
9 cause the Accused Products to produce a second light output, such as fidelity  
10 output or balanced output, at the first chromaticity, and cause the Accused  
11 Products to produce a corresponding spectral power that is different from the  
12 default brightest output (i.e., first spectral power distribution). The second power  
13 distribution approximates the target spectrum.

14           48. Elation also infringes claim 20, among other claims, of the ‘898.

15           49. Claim 20 of the ‘898 patent states:

16                   20. A controller for controlling a light output of a light fixture,

17                   the controller including a non-transitory computer readable medium  
18                   and a processor,

19                   the controller including computer executable instructions stored in the  
20                   computer readable medium for controlling operation of the controller to:

21                           energize the light fixture to produce a first light output with a  
22                           first chromaticity and a first spectral power distribution;

23                           receive an input representative of an adjustment of a lighting  
24                           effect;

25                           generate a target spectrum based on the user input; and

26                           energize the light fixture to produce a second light output with  
27                           the first chromaticity and a second spectral power distribution,

28                           the second power distribution approximates the target spectrum.

1           50. The Accused Products include a controller for controlling the light  
2 output of a light fixture, i.e., Accused Products comprise a light fixture.

3           51. The controller of the Accused Products includes a non-transitory  
4 computer readable medium, i.e., a storage device.

5           52. The controller of the Accused Products includes a processor.

6           53. The controller of the Accused Products includes computer executable  
7 instructions, i.e., software, stored in the computer readable medium for controlling  
8 operation of the controller.

9           54. The controller of the Accused Products energizes the light fixture to  
10 produce a first light output with a first chromaticity and a first spectral power  
11 distribution.

12           55. The controller of the Accused Products receives an input  
13 representative of an adjustment of a lighting effect (e.g., light quality). For  
14 example, from the brightest output setting, the Accused Products can receive a  
15 DMX value to select a balanced or fidelity output setting.

16           56. The controller of the Accused Products generates a target spectrum  
17 based on the input. For example, the controller of the Accused Products is  
18 configured to generate a target spectrum corresponding to the brightest, fidelity  
19 and balanced output settings, whichever is selected according to the input.

20           57. The controller of the Accused Products controls the light source to  
21 produce a second light output with the first chromaticity and a second spectral  
22 power distribution, the second power distribution approximating the target  
23 spectrum. For example, when starting from the brightest output, changing the  
24 Accused Products to the fidelity or balanced output will produce a different  
25 (second) spectral power distribution with the first chromaticity. The second power  
26 distribution approximates the target spectrum.

27           58. The controller of the Accused Products energizes the light fixture to  
28 produce a second light output with the first chromaticity and a second spectral

1 power distribution, the second power distribution approximates the target  
2 spectrum. For example, when starting with the default brightest output, the  
3 controller of the Accused Products energizes the light fixture to produce a second  
4 light output, such as fidelity or balanced output, at the first chromaticity and a  
5 second spectral power that is different from the default brightest output (i.e., first  
6 spectral power distribution). The second power distribution approximates the target  
7 spectrum.

8 59. Elation knew that making, using, offering to sell, selling, and/or  
9 importing the Accused Products and instructing others to use the Accused Products  
10 in an infringing manner would infringe the '898 patent. Elation's past and  
11 continued infringement of the '898 patent has been and continues to be willful and  
12 deliberate.

13 60. Because of Elation's infringement of the '898 patent, ETC has  
14 suffered and will continue to suffer irreparable harm and monetary damages, which  
15 continue to accrue, in an amount to be determined at trial.

16 61. Elation's willful infringement will continue unless enjoined by this  
17 Court.

### 18 **COUNT III**

#### 19 **Patent Infringement of the '519 patent**

20 62. ETC realleges and incorporates the foregoing paragraphs as though  
21 fully set forth herein.

22 63. ETC has the right to enforce the '519 patent and right to recover  
23 damages for infringement.

24 64. Elation has directly infringed one or more claims of the '519 patent by  
25 making, using, offering to sell and/or importing the Accused Products.

26 65. With knowledge of the '519 patent, Elation has induced infringement  
27 of one or more claims of the '519 patent by actively encouraging others to make,  
28

1 use, offer to sell, sell and/or import the Accused Products knowing that such  
2 encouragement would result in direct infringement by others.

3 66. With knowledge of the '519 patent, Elation has contributed to  
4 infringement of one or more claims of the '519 patent by providing the Accused  
5 Products to others knowing that the Accused Products are a material part of the  
6 invention and especially made for use in a manner that infringes the '519 patent,  
7 and not a staple article or commodity of commerce suitable for substantial  
8 noninfringing use.

9 67. By way of example, Elation's and others' use of the Accused Products  
10 infringes claim 1 of the '519 patent.

11 68. Claim 1 of the '519 patent states:

12 1. A lighting control system comprising:

13 one or more light sources;

14 one or more driver circuits configured to provide  
15 drive signals to the one or more light sources;

16 an interface configured to receive an input related  
17 to a light output of the one or more light sources, the  
18 input being related to an adjustment of a lighting effect;  
19 and

20 a controller connected to the one or more driving  
21 circuits and the interface, the controller including a  
22 processor and a memory, the controller configured to:

23 control the one or more light sources to  
24 produce a first light output with a first chromaticity  
25 and a first spectral power distribution,

26 receive the input related to the adjustment of  
27 the lighting effect,

28 generate a target spectrum based on the  
input, and

1 control the one or more light sources to  
2 produce a second light output with the first  
3 chromaticity and a second spectral power  
4 distribution, the second power distribution  
approximating the target spectrum.

5 69. The Accused Products are part of lighting control system.

6 70. The Accused Products have one or more light sources, including red,  
7 green blue, mint and amber LEDs.

8 71. The Accused Products have one or more driver circuits configured to  
9 provide drive signals to the light sources that control the output of the light  
10 sources.

11 72. The Accused Products include an interface configured to receive an  
12 input related to light out of the one or more light sources, the input being related to  
13 an adjustment of a lighting effect (e.g., light quality). For example, the Accused  
14 Products are part of a system that includes an interface in which the interface  
15 receives inputs from the user relating to the output from the light sources, the input  
16 being related to an adjustment of a lighting effect, such as selecting the brightest,  
17 balanced and fidelity output settings.

18 73. The Accused Products have a controller with a processor and memory  
19 connected to the driving circuits.

20 74. The controller of the Accused Products is configured to control the  
21 light sources to produce a first light output with a first chromaticity, i.e., a selected  
22 color and output setting (e.g., brightest) having a spectral power distribution for  
23 the selected color.

24 75. The controller of the Accused Products is configured to receive the  
25 input related to the adjustment of the lighting effect. For example, starting from the  
26 brightest output, a DMX signal can be sent to and received by the controller to  
27 adjust the lighting effect to, for example, the fidelity or the balanced output setting.

1           76. The controller of the Accused Products is configured to generate a  
2 target spectrum based on the input. For example, the controller of the Accused  
3 Products is configured to generate a target spectrum corresponding to the brightest,  
4 fidelity and balanced output settings, whichever is selected according to the input.

5           77. The controller of the Accused Products is configured to control the  
6 one or more light sources to produce a second light output with the first  
7 chromaticity and a second spectral power distribution, the second power  
8 distribution approximating the target spectrum. For example, when starting from  
9 the brightest output, changing the Accused Products to the fidelity or balanced  
10 output will produce a different (second) spectral power distribution with the first  
11 chromaticity. The second power distribution approximates the target spectrum.

12           78. The Accused Product also infringe claim 19, among other claims, of  
13 the '519 patent.

14           79. Claim 19 of the '519 patent states:

15               19. A controller for controlling a light output of a light source,

16               the controller including a non-transitory computer readable medium  
17 and a processor,

18               the controller including computer executable instructions stored in the  
19 computer readable medium for controlling operation of the controller to:

20               control the light source to produce a first light output with a first  
21 chromaticity and a first spectral power distribution;

22               receive an input related to an adjustment of a lighting effect;

23               generate a target spectrum based on the input; and  
24

25               control the light source to produce a second light output with the first  
26 chromaticity and a second spectral power distribution, the second power  
27 distribution approximating the target spectrum.

1           80. The Accused Products include a controller for controlling the light  
2 output of light source, i.e., the five LEDs of the Accused Products.

3           81. The controller of the Accused Products includes a non-transitory  
4 computer readable medium, i.e., a storage device.

5           82. The controller of the Accused Products includes a processor.

6           83. The controller of the Accused Products includes computer executable  
7 instructions, i.e., software, stored in the computer readable medium for controlling  
8 operation of the controller.

9           84. The controller of the Accused Products controls the light source to  
10 produce a first light output with a first chromaticity and a first spectral power  
11 distribution.

12           85. The controller of the Accused Products receives an input related to an  
13 adjustment of a lighting effect (e.g., light quality), such as selecting the brightness,  
14 fidelity and balanced output settings.

15           86. The controller of the Accused Products generates a target spectrum  
16 based on the input. For example, the controller of the Accused Products is  
17 configured to generate a target spectrum corresponding to the brightest, fidelity  
18 and balanced output settings, whichever is selected according to the input.

19           87. The controller of the Accused Products controls the light source to  
20 produce a second light output with the first chromaticity and a second spectral  
21 power distribution, the second power distribution approximating the target  
22 spectrum. For example, when starting from the brightest output, changing the  
23 Accused Products to the fidelity or balanced output will produce a different  
24 (second) spectral power distribution with the first chromaticity. The second power  
25 distribution approximates the target spectrum.

26           88. Elation knew that making, using, offering to sell, selling, and/or  
27 importing the Accused Products and instructing others to use the Accused Products  
28 in an infringing manner would infringe the '519 patent. Elation's past and

1 continued infringement of the '519 patent has been and continues to be willful and  
2 deliberate.

3 89. Because of Elation's infringement of the '519 patent, ETC has  
4 suffered and will continue to suffer irreparable harm and monetary damages, which  
5 continue to accrue, in an amount to be determined at trial.

6 90. Elation's willful infringement will continue unless enjoined by this  
7 Court.

8 **PRAYER FOR RELIEF**

9 WHEREFORE, ETC respectfully prays that upon trial on the merits this  
10 Court render judgment in ETC's favor and against Elation as follows:

11 A. Judgment that Elation has infringed the '074 patent, the '898 patent,  
12 and the '519 patent under 35 U.S.C. § 271;

13 B. A preliminary and permanent injunction pursuant to 35 U.S.C. § 283,  
14 preventing Elation, its officers, agents, servants, employees, successors, assignees,  
15 parents, subsidiaries, affiliated or related companies, attorneys, and all others in  
16 active concert or participation with any of them from further infringing the '074  
17 patent, the '898 patent, and the '519 patent;

18 C. An award of damages adequate to compensate ETC for Elation's  
19 patent infringement, and no less than the damages provided under 35 U.S.C. § 284;

20 D. An award for enhanced damages under 35 U.S.C. § 284;

21 E. An award for attorneys' fees under 35 U.S.C. § 285;

22 F. An award of pre-judgment interest, post-judgment interest, and all  
23 costs associated with this action; and

24 G. Any other relief as the Court deems appropriate and just under the  
25 circumstances.

26

27

28



**JURY TRIAL DEMAND**

ETC demands a trial by jury on all matters and issues properly tried to a jury pursuant to Federal Rules of Civil Procedure 38 and 39, and other applicable federal and state law.

Dated: January 31, 2025

SHANE A. BRUNNER  
MICHAEL BEST & FRIEDRICH LLP

KARIN G. PAGNANELLI  
MITCHELL SILBERBERG & KNUPP LLP

By: /s/ Karin G. Pagnanelli  
Karin G. Pagnanelli (SBN 174763)  
Attorneys for Plaintiff  
Electronic Theatre Controls, Inc. d/b/a  
ETC

# Exhibit A

(12) **United States Patent**  
**Hatley et al.**

(10) **Patent No.:** **US 8,593,074 B2**  
(45) **Date of Patent:** **Nov. 26, 2013**

(54) **SYSTEMS AND METHODS FOR CONTROLLING AN OUTPUT OF A LIGHT FIXTURE**

6,967,447 B2 11/2005 Lim et al.  
7,012,382 B2 3/2006 Cheang et al.  
7,023,543 B2 4/2006 Cunningham  
7,030,574 B2 4/2006 Lim et al.  
7,067,995 B2 6/2006 Gunter et al.

(75) Inventors: **Troy Bryan Hatley**, Lodi, WI (US);  
**Timothy George Robbins**, Lodi, WI (US); **Mike Wood**, Austin, TX (US)

(Continued)

#### FOREIGN PATENT DOCUMENTS

(73) Assignee: **Electronic Theater Controls, Inc.**, Middleton, WI (US)

DE 102007059130 6/2009  
JP 20098110715 5/2009

(Continued)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 445 days.

#### OTHER PUBLICATIONS

International Preliminary Report on Patentability for Application No. PCT/US2011/063965 dated Jan. 15, 2013 (5 pages).

(21) Appl. No.: **13/004,922**

(Continued)

(22) Filed: **Jan. 12, 2011**

(65) **Prior Publication Data**

US 2012/0176063 A1 Jul. 12, 2012

Primary Examiner — David H Vu

(74) Attorney, Agent, or Firm — Michael Best & Friedrich LLP

(51) **Int. Cl.**  
**H05B 37/00** (2006.01)

(52) **U.S. Cl.**  
USPC ..... **315/291**; 315/307; 315/308; 315/312

(58) **Field of Classification Search**  
USPC ..... 315/291, 307, 308, 312, 314, 316, 319, 315/317, 318  
See application file for complete search history.

(57) **ABSTRACT**

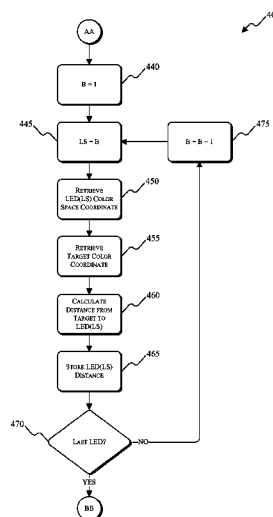
Systems and methods for controlling an output of a light fixture. A light fixture of one construction includes four or more light sources and is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on one or more input parameters. The input parameters correspond to, for example, a desired target color and an intensity for the desired target color. A white point setting is determined based on the one or more input parameters and a relationship between the one or more input parameters and the color temperature of an ideal black-body radiator. A color temperature transform is selected based on the white point color temperature setting, and is used to determine a color coordinate corresponding to a modified target color. A set of light source output values corresponding to the modified target color are identified, and the light sources are driven to the identified output values.

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**20 Claims, 9 Drawing Sheets**



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*FIG. 1*

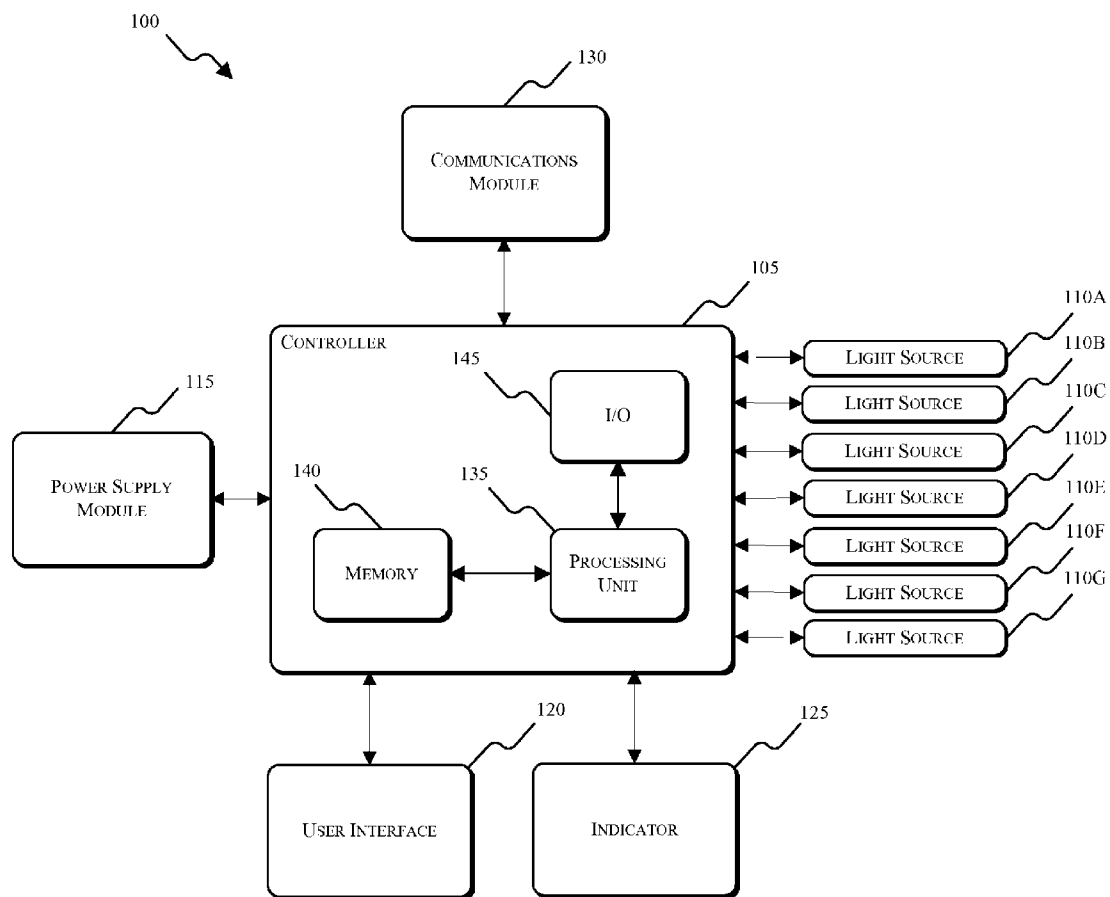


FIG. 2

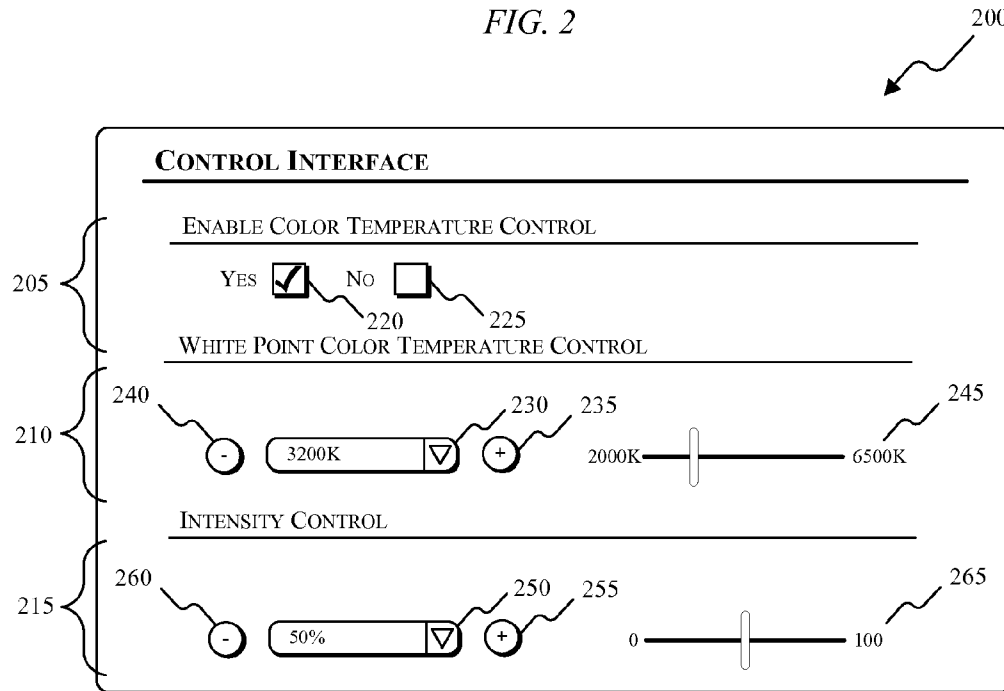


FIG. 3

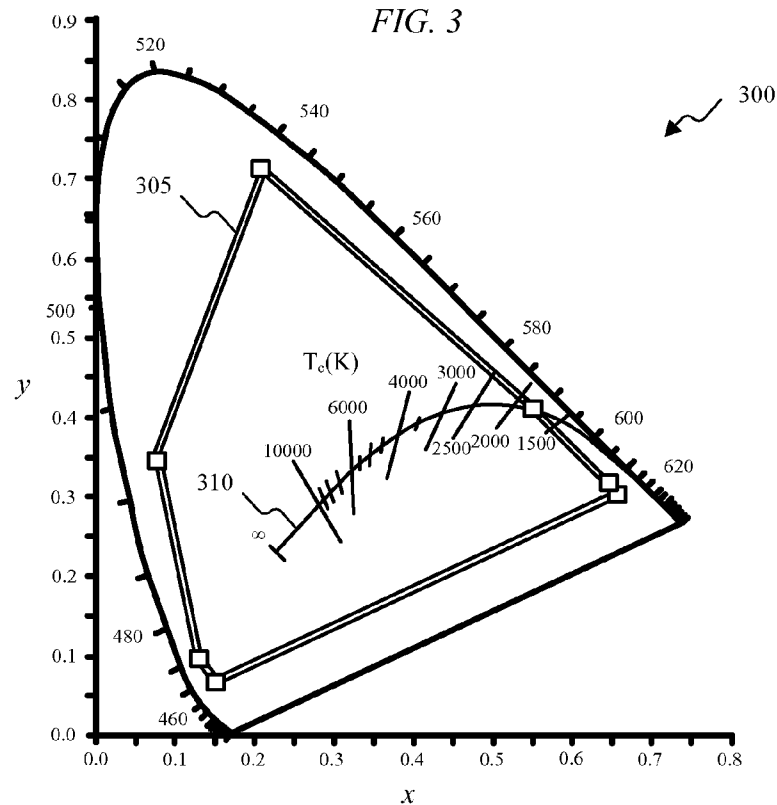
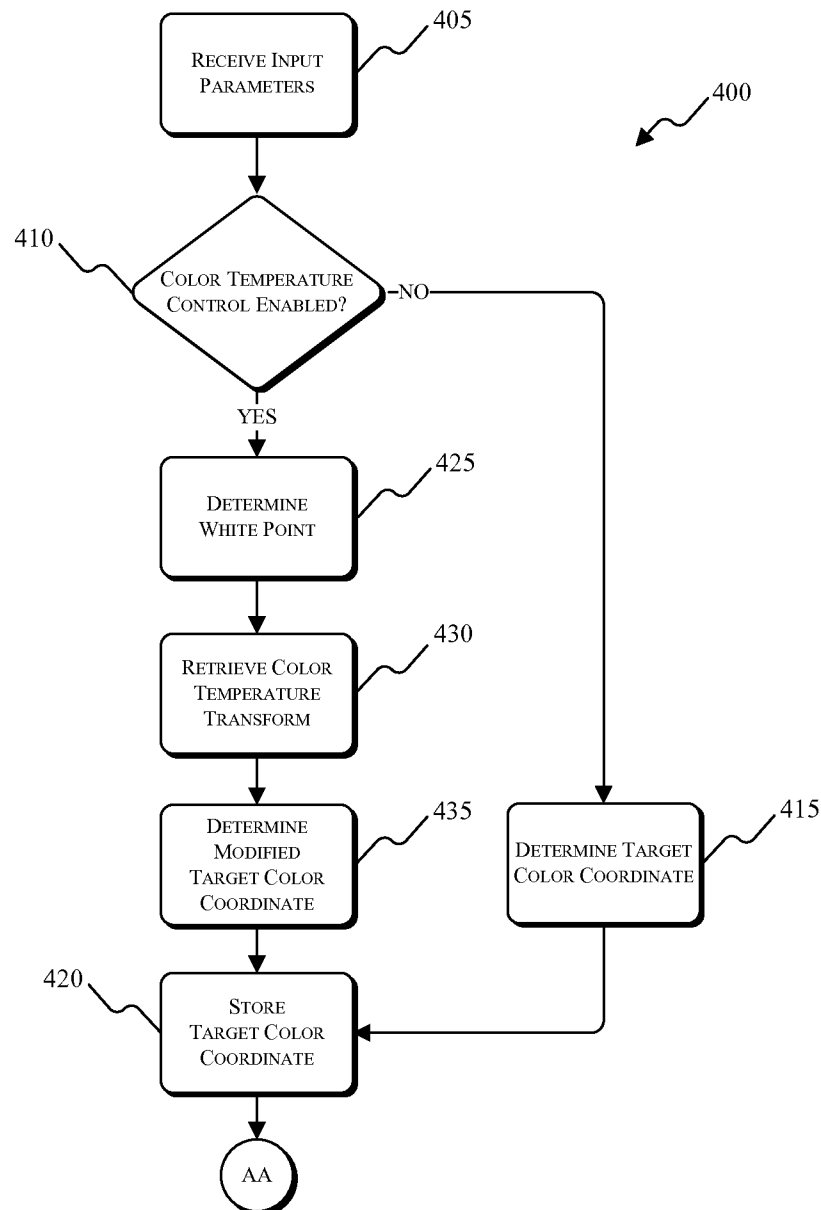


FIG. 4



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FIG. 5

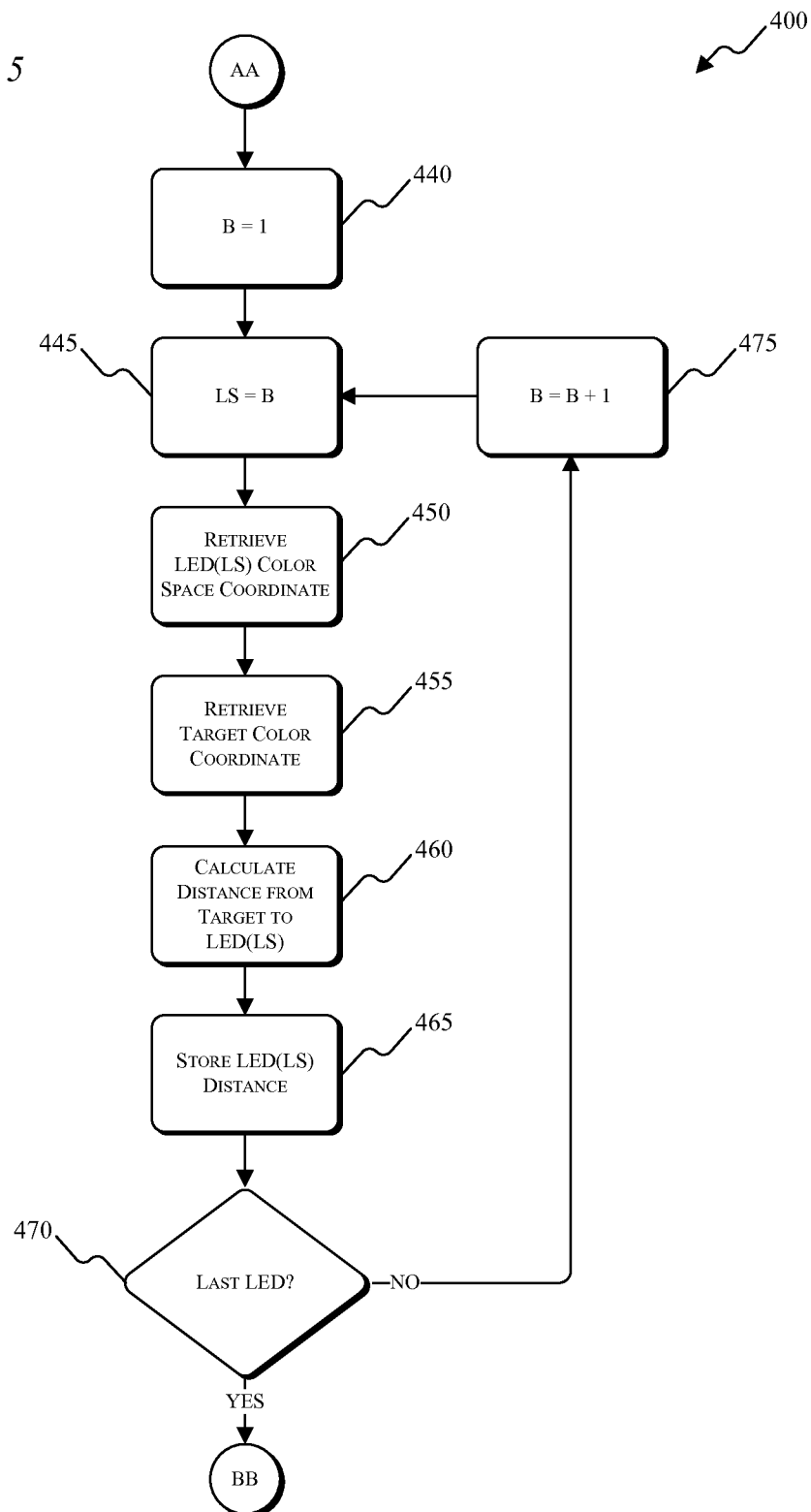




FIG. 6

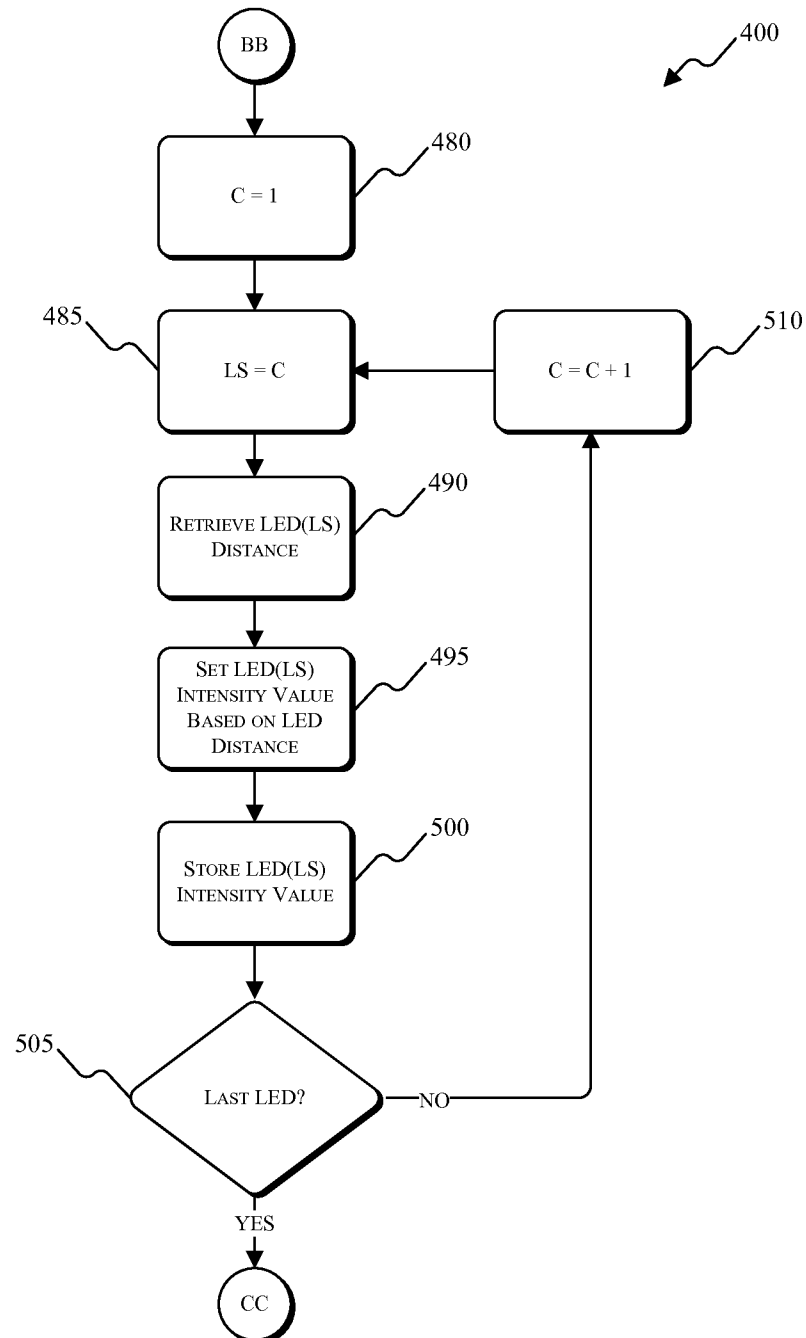
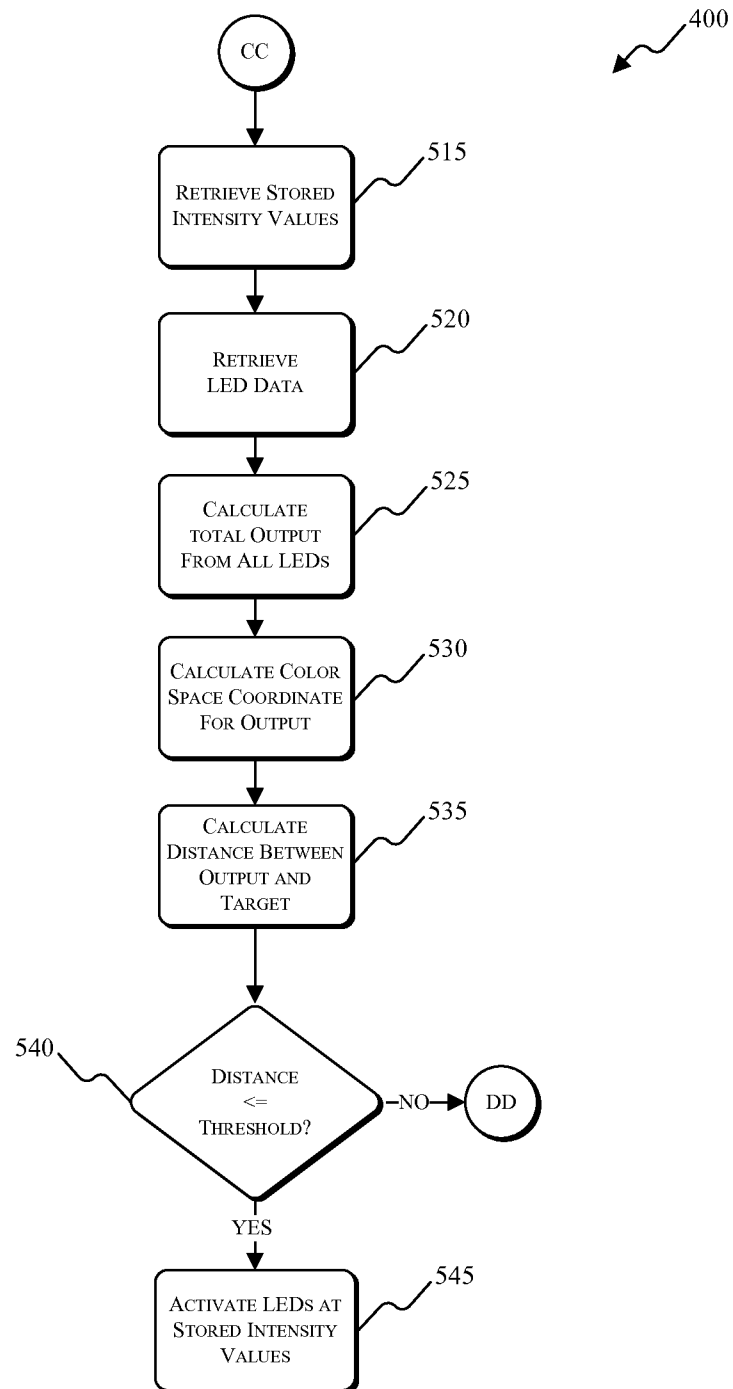


FIG. 7



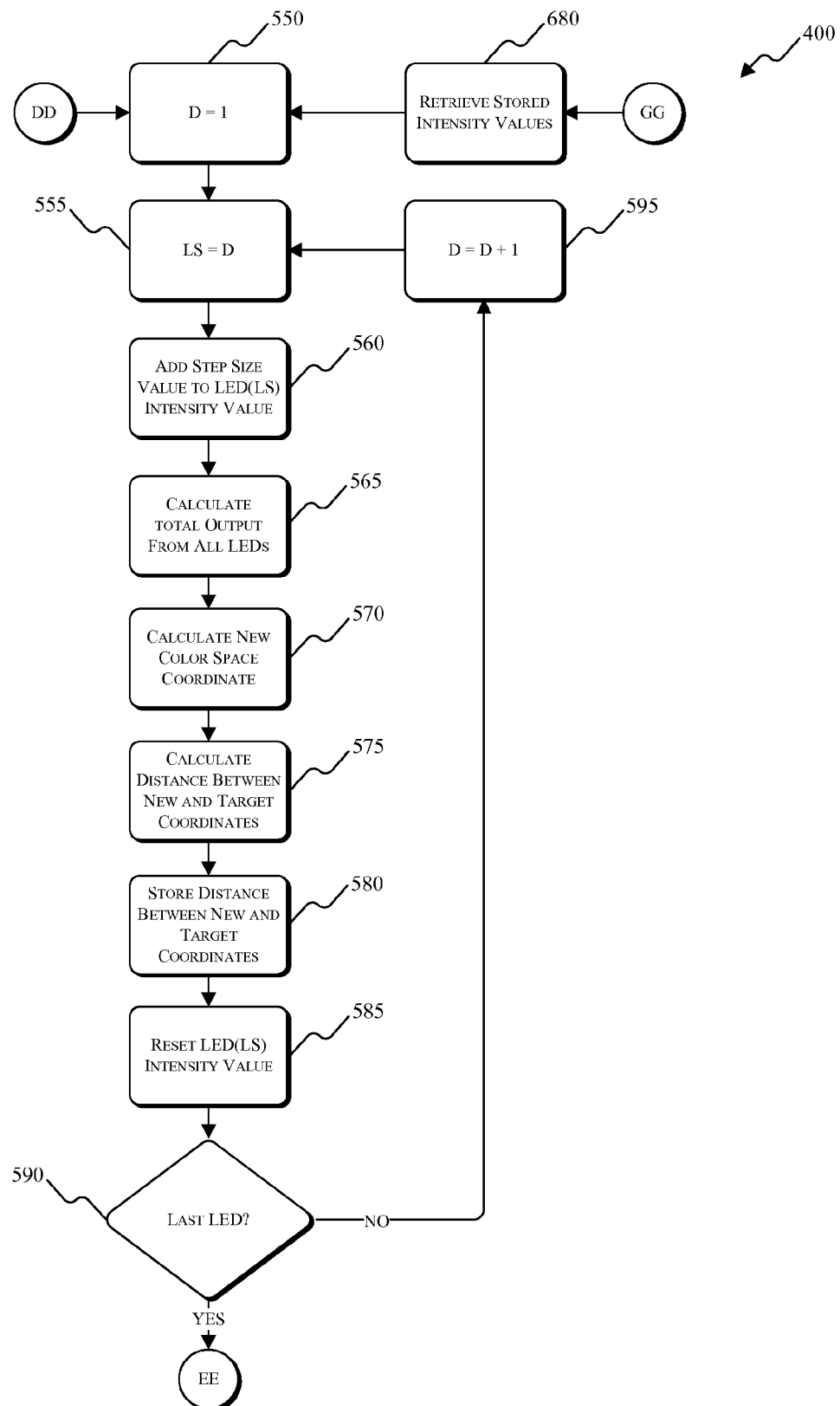
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FIG. 8



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FIG. 9

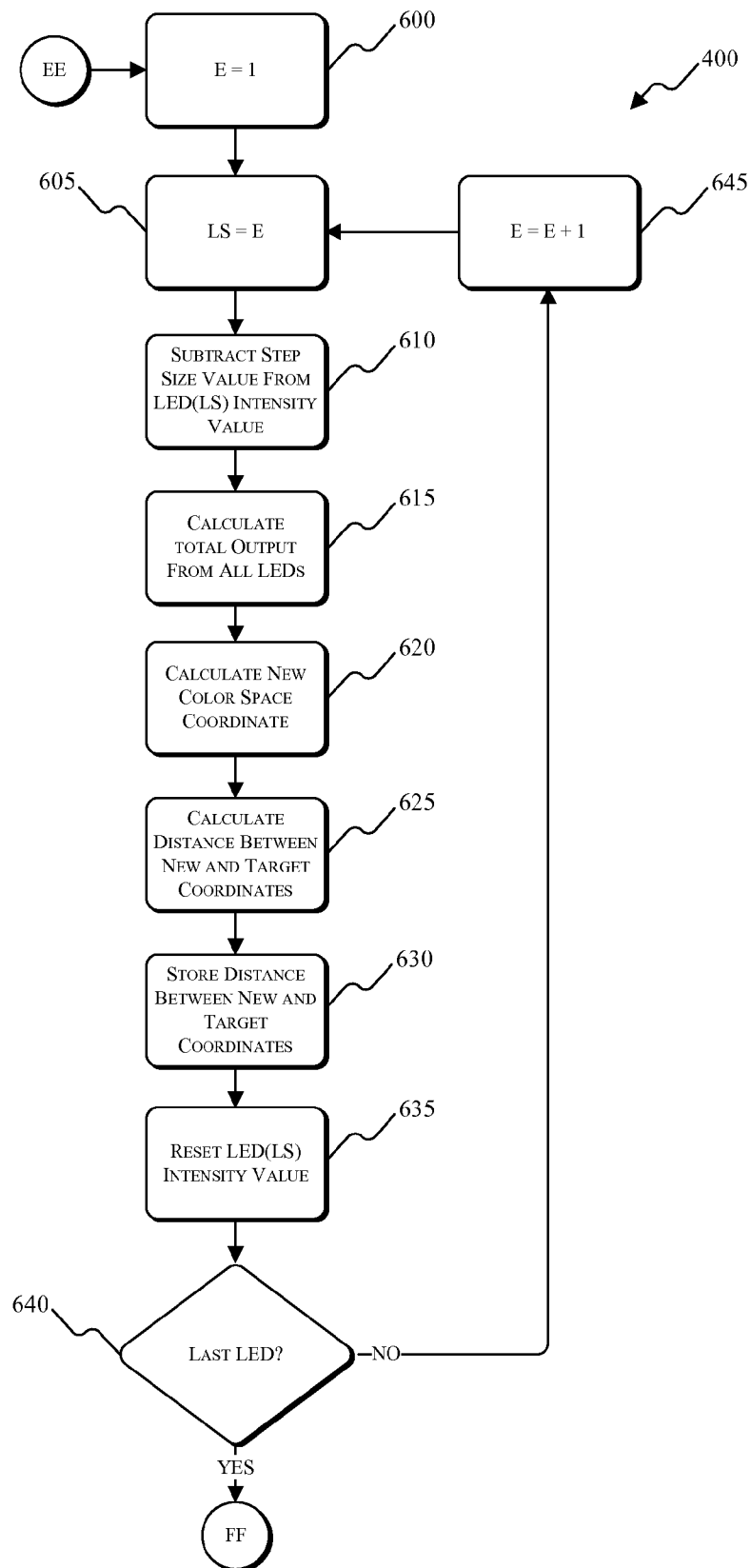
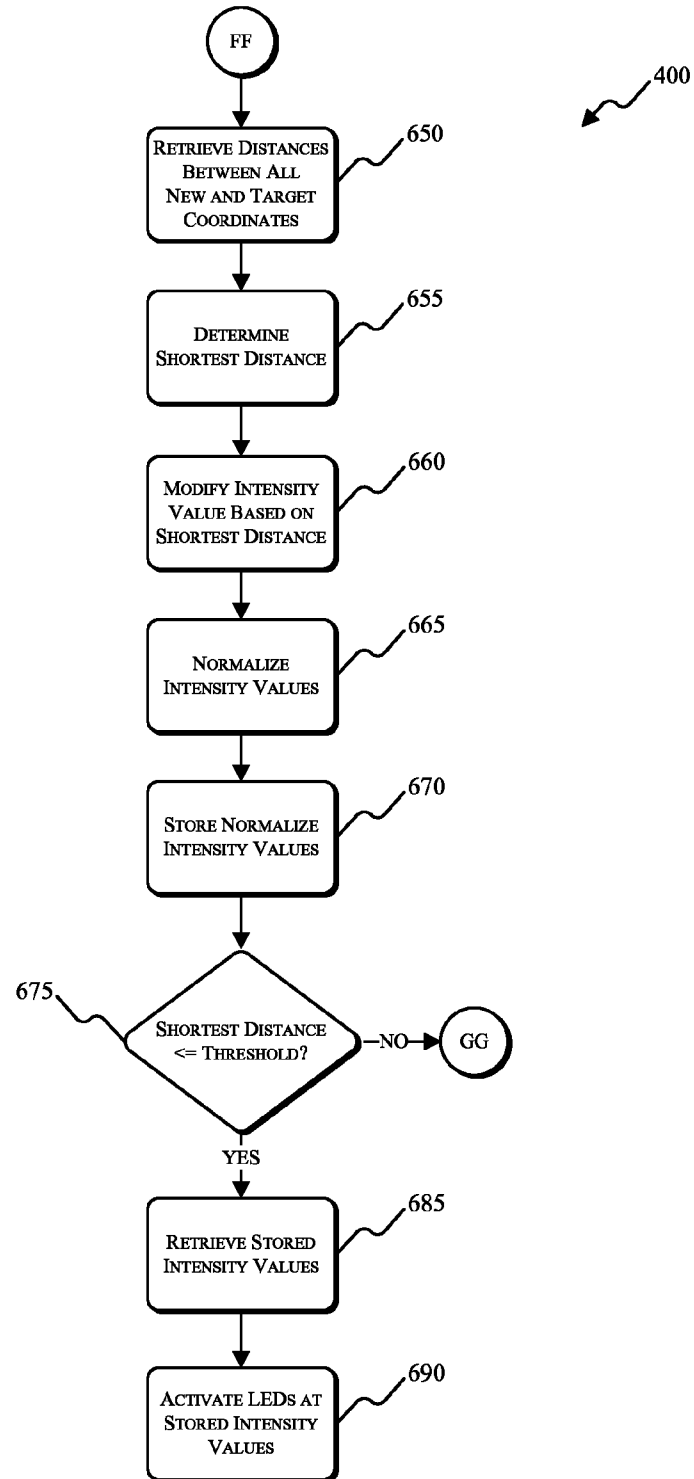


FIG. 10



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# 1

## SYSTEMS AND METHODS FOR CONTROLLING AN OUTPUT OF A LIGHT FIXTURE

### BACKGROUND

This invention relates to controlling an output of a light fixture.

The color temperature of a white-light light source (e.g., an incandescent light bulb) corresponds to the temperature of an ideal black-body radiator that radiates light of a comparable hue, and is identified in units of absolute temperature, Kelvin ("K"). Color temperatures of approximately 5,000K or greater are referred to as cool colors, and color temperatures between approximately 2,700K and 3,000K are referred to as warm colors. For example, the light output by an incandescent light bulb is thermal radiation and approximates an ideal black-body radiator. The color temperatures associated with the incandescent light bulb follow the Planckian locus through a particular color space (e.g., the CIE xyY color space) from low color temperatures (i.e., warm colors) to high color temperatures (i.e., cool colors). Accordingly, color temperature is a convenient way to describe the output of an incandescent light bulb or other similar white-light light sources.

### SUMMARY

Although color temperature is convenient for describing the output of white-light light sources, color temperature is undefined with respect to light sources that do not approximate, or cannot be correlated to, ideal black-body radiators (e.g., red light emitting diodes ("LEDs"), green LEDs, blue LEDs, etc.). Such light sources cannot be individually described with respect to a color temperature. Although systems have been developed that use discrete color light sources (e.g., LEDs) to approximate white-light light sources, such systems are unable to produce a non-white output that mimics the color temperature changes of an ideal black-body radiator.

As such, the invention provides systems and methods for controlling an output of a light fixture. The light fixture includes four or more light sources. The light fixture, or a controller connected to the light fixture, is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on a desired target color, a white point color temperature setting, and an intensity value. For example, input parameters corresponding to the desired target color and the intensity for the desired target color are inputted using a color control methodology (e.g., HSI, RGB, etc.). The white point color temperature setting is then determined based on the intensity value and a relationship between the intensity value and the color temperature of an ideal black-body radiator. A color temperature transform is then determined, selected, or identified based on the white point color temperature setting. The color temperature transform and the desired target color are used to determine a modified target color point within a color space (e.g., the CIE xyY color space). A set of light source output intensity values corresponding to the modified target color point are then identified, and the light sources are driven to the identified output intensity values.

In one implementation, the invention provides a method of controlling an output of a light fixture. The light fixture includes four or more light sources. The method includes

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receiving a first input parameter corresponding to a first color point within a color space, receiving a second input parameter associated with a desired intensity for the first color point, and determining a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator. The white point corresponds to a second color point within the color space, and a color temperature transform is selected based on the white point. The method also includes calculating a third color point within the color space based on the color temperature transform, determining a respective light source output value for each of the four or more light sources based on the third color point, and driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point.

In another implementation, the invention provides a method of controlling an output of a light fixture. The light fixture includes four or more light sources. The method includes receiving a set of input parameters. The set of input parameters correspond to a first color point within a color space and an intensity for the first color point. The method also includes determining a color temperature setting based on a relationship between the set of input parameters and the color temperature of a black-body radiator. The color temperature setting corresponds to a second color point within the color space. A color temperature transform is determined based on the color temperature setting, and a third color point within the color space is calculated based on the color temperature transform. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point. The method also includes determining a respective light source output value for each of the four or more light sources based on the third color point, and driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

In one construction, the invention provides a system for controlling the output of a light fixture. The system includes four or more light sources and a controller. The controller is configured to receive a first input parameter corresponding to a first color point within a color space, receive a second input parameter associated with a desired intensity for the first color point, and determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator. The white point corresponds to a second color point within the color space, and a color temperature transform is selected based on the white point. The controller is also configured to calculate a third color point within the color space based on the color temperature transform, determine a respective light source output value for each of the four or more light sources based on the third color point, and drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture. The color temperature transform defines a relationship between the first color point and the third color point. The third color point is different than the first color point, and the third color point is different than the second color point.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

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## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a light fixture.

FIG. 2 is a control interface according to an embodiment of the invention.

FIG. 3 is the International Commission on Illumination ("CIE") 1931 color space chromaticity diagram and illustrates a gamut of a light fixture.

FIGS. 4-10 are a process for controlling an output of a light fixture.

## DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

The invention described herein relates to systems and methods for controlling an output of a light fixture. The light fixture includes four or more light sources. The light fixture, or a controller connected to the light fixture, is configured to produce an output that mimics the color temperature changes of an ideal black-body radiator based on one or more input parameters (e.g., a desired target color, a white point color temperature setting, an intensity value, etc.). For example, the input parameters corresponding to a desired target color and an intensity value for the desired color are inputted using one or more color control methodologies (e.g., HSI, RGB, etc.). The desired target color corresponds to a first color point or coordinate within a color space (e.g., the CIE xyY color space), and the intensity value corresponds to an intensity for the first color point. The white point color temperature setting is then determined, selected, or calculated based on, for example, the intensity value and a relationship between the intensity value and the color temperature of an ideal black-body radiator. The white point color temperature setting corresponds to a second color point or coordinate within the color space and is used to determine, select, or identify a color temperature transform. The color temperature transform defines a relationship between the first color point and a third color point or coordinate. The color temperature transform is then used to determine the third color point within the color space. The third color point is different from the first color point and the second color point. A set of light source output intensity values corresponding to the third color point are then identified, and the light sources are driven to the identified output intensity values.

In some implementations, light fixtures are used in, for example, a theatre, a hall, an auditorium, a studio, or the like. Each light fixture 100 includes, among other things, a controller 105, a plurality of light sources 110A-110G, a power supply module 115, a user interface 120, one or more indicators 125, and a communications module 130, as shown in FIG. 1. In the illustrated construction, the light fixture 100 includes seven light sources 110A-110G. Each light source is configured to generate light at a specific wavelength or range of wavelengths. For example, the light sources 110A-110G generate light corresponding to the colors red, red-orange, amber, green, cyan, blue, and indigo. In other constructions, light sources that generate different colors are used (e.g., violet, yellow, etc.).

The controller 105 includes, or is connected to an external device (e.g., a computer), which includes combinations of software and hardware that are operable to, among other

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things, control the operation of one or more of the light fixtures, control the output of each of the light sources 110A-110G, and activate the one or more indicators 125 (e.g., LEDs or a liquid crystal display ("LCD")). In one construction, the controller 105 or external device includes a printed circuit board ("PCB") (not shown) that is populated with a plurality of electrical and electronic components that provide power, operational control, and protection to the light fixtures. In some constructions, the PCB includes, for example, a processing unit 135 (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory 140, and a bus. The bus connects various components of the PCB including the memory 140 to the processing unit 135. The memory 140 includes, for example, a read-only memory ("ROM"), a random access memory ("RAM"), an electrically erasable programmable read-only memory ("EEPROM"), a flash memory, a hard disk, or another suitable magnetic, optical, physical, or electronic memory device. The processing unit 135 is connected to the memory 140 and executes software that is capable of being stored in the RAM (e.g., during execution), the ROM (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Additionally or alternatively, the memory 140 is included in the processing unit 135. The controller 105 also includes an input/output ("I/O") system 145 that includes routines for transferring information between components within the controller 105 and other components of the light fixtures or system. For example, the communications module 130 is configured to provide communication between the light fixture 100 and one or more additional light fixtures or another control device within a lighting system.

Software included in the implementation of the light fixture 100 is stored in the memory 140 of the controller 105. The software includes, for example, firmware, one or more applications, program data, one or more program modules, and other executable instructions. The controller 105 is configured to retrieve from memory and execute, among other things, instructions related to the control processes and methods described below. For example, the controller 105 is configured to execute instructions retrieved from the memory 140 for performing a mathematical transformation of a control value to a value that is required to drive the light sources 110A-110G to produce a desired color. In other constructions, the controller 105 or external device includes additional, fewer, or different components.

The PCB also includes, among other things, a plurality of additional passive and active components such as resistors, capacitors, inductors, integrated circuits, and amplifiers. These components are arranged and connected to provide a plurality of electrical functions to the PCB including, among other things, filtering, signal conditioning, or voltage regulation. For descriptive purposes, the PCB and the electrical components populated on the PCB are collectively referred to as the controller 105.

The user interface 120 is included to control the light fixture 100 or the operation of a lighting system as a whole. The user interface 120 is operably coupled to the controller 105 to control, for example, the output of the light sources 110A-110G. The user interface 120 can include any combination of digital and analog input devices required to achieve a desired level of control for the system. For example, the user interface 120 can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some constructions, the user interface is separated from the light fixture 100.



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The power supply module **115** supplies a nominal AC or DC voltage to the light fixture **100** or system of light fixtures. The power supply module **115** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power supply module **115** is also configured to supply lower voltages to operate circuits and components within the light fixture **100**. In other constructions, the light fixture **100** is powered by one or more batteries or battery packs.

As illustrated in FIG. 1, the controller **105** is connected to light sources **110A-110G**. In other constructions, the controller **105** is connected to, for example, red, green, and blue ("RGB") light sources, red, green, blue, and amber ("RGBA") light sources, red, green, blue, and white ("RGBW") light sources, or other combinations of light sources. A seven light source implementation is illustrated because it is operable to reproduce substantially the entire spectrum of visible light. In other implementations, eight or more light sources are used to further enhance the light fixtures ability to reproduce visible light.

FIG. 2 illustrates a control interface **200** for controlling the color temperature of the output of the light fixture **100**. In some constructions, the control interface **200** is included in the user interface **120**. The control interface **200** is, for example, a graphical user interface ("GUI") that is displayed on a monitor or a similar display. In some constructions, the control interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like. The illustrated control interface **200** includes an enable color temperature control section **205**, a white point color temperature control section **210**, and an intensity control section **215**. Although the intensity control section **215** is illustrated as being separate from, for example, target color controls (e.g., hue control, saturation control, individual light source control, etc.), the intensity control section **215** can alternatively be included with the target color controls. The enable color temperature control section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect automatic color temperature control. As described in greater detail below, the automatic color temperature control is configured to automatically modify a user selected target color to mimic the color temperature changes of an ideal black-body radiator. Once enabled, the color temperature control can use a white point setting from the white point color temperature control section **210** to modify a target color to produce an output of the light fixture that mimics the color temperature changes of a black-body radiator. Additionally or alternatively, an intensity setting from the intensity control section **215** can be used to modify a target color to produce an output of the light fixture that mimics the color temperature changes of a black-body radiator.

The white point color temperature control section **210** includes a white point input portion **230**, an increment button **235**, a decrement button **240**, and a fader **245**. The white point input portion **230** is controlled by directly selecting and modifying a white point setting for the output of the light fixture. For example, a user is able to modify or populate the white point input portion **230** with a desired white point color temperature (i.e., a value in Kelvin). The user populates the white point input portion **230** by entering text via a mechanical or virtual keyboard of a computer or similar processing device, and using a pointing or selection device such as a mouse to control a cursor on the display. Input signals from the keyboard and the mouse are received, processed, and translated into a visual result or action in the interface **200**. For example, if the user enters text using a keyboard, the activated keys

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produce signals which are represented as type-written text in the interface **200**. Similarly, a mouse click, which corresponds to a location of the cursor on the screen, results in selecting/deselecting the increment button **235**, the decrement button **240**, a dropdown menu, the position of the fader **245**, etc. In other implementations, the interface **200** is accessed and controlled using a touch-screen device and a user's finger strokes or tapping are used to populate or modify the white point input portion **230**.

Like the white point color temperature control section **210**, the intensity control section **215** includes an intensity input portion **250**, an increment button **255**, a decrement button **260**, and a fader **265**. The intensity input portion **250** is controlled by directly selecting and modifying an intensity setting or value for the target color. For example, a user is able to modify or populate the intensity input portion **250** with a desired intensity setting or value (e.g., a percent). The intensity input portion **250** is modified or populated in a manner similar to that described above with respect to the white point input portion **230**.

FIG. 3 illustrates the CIE xyY color space **300** and the available color gamut **305** for the light fixture **100**. As such, only colors that fall within or on the illustrated color gamut **305** are reproducible by the light fixture **100**. Also illustrated is the Planckian locus **310**, which illustrates the various color temperatures for an idea black-body radiator.

The CIE xyY color space **300** represents x-coordinates with values between 0.0 and 0.8, and y-coordinates with values between 0.0 and 0.9. To avoid floating point calculations, 16-bit integers are used in some constructions to represent both the x-coordinate and the y-coordinate. An integer value of zero corresponds to a coordinate of 0.0, and an integer value of 32,767 corresponds to a coordinate of 1.0. Therefore, some constructions of the invention achieve a resolution of  $1/32,767$  or approximately 0.00003.

The invention can be implemented using a variety of color control, targeting, and matching methodologies, such as HSI, RGB, CYM, YIQ, YUV, HSV, HLS, XYZ, etc. The techniques described below are exemplary, and other techniques for controlling the output of the light fixture **100** to mimic the color temperature changes of an ideal black-body radiator are within the spirit and scope of the invention. Additionally, the invention is capable of being implemented internal to or external from the light fixture **100**. For example, the light fixture **100** can include sufficient memory and processing power to execute one or more programs associated with the inventive methods. Additionally or alternatively, a separate computer (e.g., a central computer, a control panel, a controller, etc.) includes sufficient memory and processing power to execute one or more programs associated with the inventive methods.

FIGS. 4-10 are a process **400** for controlling an output of a light fixture to mimic the color temperature changes of an ideal black-body radiator. The steps of the process **400** are described in an iterative manner for descriptive purposes. Various steps described herein with respect to the process **400** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial and iterative manner of execution. A target color and various parameters associated with the target color, the output of the light fixture, settings of the light fixture, etc. are inputted as one or more input parameters (e.g., a set of input parameters) (step **405**) to the light fixture using a complex color control methodology (e.g., HSI, RGB, etc.). The target color corresponds to a target color point or coordinate within a color space, such as the CIE xyY color space. The input parameters are received from, for example, a controller or user interface (e.g., the user interface



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120), which allows a user to enter a desired target color, a hue setting, a saturation setting, a white point setting, an intensity setting, individual light source settings, etc. Additionally or alternatively, the controller receives or retrieves a desired target color, a hue setting, a saturation setting, a white point setting, an intensity setting, individual light source settings, etc. from memory (e.g., as part of a program or sequence of desired colors and settings). In some implementations, the input parameters can be stored in either a volatile or non-volatile memory. For example, if one or more of the input parameters have already been stored to a non-volatile memory (e.g., a ROM), the stored one or more input parameters can be retrieved and stored in, for example, a RAM or similar memory used to store information necessary for the execution of the process 400.

Following step 405, light fixture 100 or a controller connected to the light fixture 100 determines whether color temperature control is enabled (step 410). For example, the color temperature control can be enabled using the control interface 200 described above with respect to FIG. 2. In some implementations, selecting the YES checkbox 220 in FIG. 2 causes an indicator (e.g., a flag, a bit, etc.) to be set. In such implementations, a flag or a bit set to a value of "1" can indicate that the color temperature control is enabled. In other implementations, setting the YES checkbox 220 sets a software pointer to a desired program associated with color temperature control. For example, if the NO checkbox 225 in FIG. 2 is selected, the pointer points to, or causes to be accessed, a software program that does not include executable instructions for controlling the output of the light fixture to mimic color temperature changes. If the YES checkbox 220 is selected, the pointer points to, or causes to be accessed, a software program that includes executable instructions associated with the control of the output of the light fixture to mimic color temperature changes.

If, at step 410, the color temperature control is not enabled, the input parameters are used to determine a target color point or coordinate (step 415) within a color space (e.g., the CIE xyY color space) using, for example, a standard color space conversion (e.g., based on tristimulus values). The target color coordinate substantially corresponds to the desired target color. The tristimulus values correspond to the amounts of three primary colors in a three-component additive color model that are needed to match a target color. The tristimulus values, denoted by X, Y, and Z, are derived parameters that are used to represent the human eye's response to red, green, and blue colors and are calculated using three corresponding color matching functions. The target color coordinate is determined based on the calculated tristimulus values and includes an x-coordinate and a y-coordinate which correspond to a location within the color space (see FIG. 3). The target color coordinate is then stored in memory (step 420).

If the color temperature control is enabled at step 410, a white point color temperature setting for the output of the light fixture is determined (step 425). The white point color temperature setting corresponds to a white point color coordinate within the color space that substantially lies on the Planckian locus. In some implementations, the white point color coordinate is different from the target color coordinate (e.g., the target color coordinate does not substantially lie on the Planckian locus). In other implementations, the white point color coordinate is the same as the target color coordinate. As described above, the control interface 200 can be used to set or select a white point color temperature or an intensity value. Additionally or alternatively, a predetermined or preselected white point color temperature setting (e.g., a default white point color temperature setting) can be retrieved

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from memory. In some implementations, the intensity value is used to determine the white point color temperature setting. For example, depending on the intensity value, one of a plurality of calculated or predetermined white point color temperatures is selected. In other implementations, a white point color temperature is selected using the control interface 200, and the intensity value is used to scale the selected white point color temperature. For example, the selected white point color temperature can be set as a maximum white point color temperature. As the intensity value is decreased, the user-selected white point color temperature is decreased. Additional selection techniques can also be used. For example, the user-selected white point color temperature may correspond to 50% intensity. In such an implementation, as the intensity value is increased, the white point color temperature is increased, and as the intensity value is decreased, the white point color temperature is decreased.

In some implementations, the white point color temperature setting is set using the intensity input portion 250 described above with respect to FIG. 2. For example, the intensity input portion 250 and the control interface 200 are used to generate a signal corresponding to a desired intensity value (i.e., an input parameter) that is received by a controller (e.g., the controller 105). The desired intensity value is correlated to a color temperature based on one or more relationships (e.g., estimations, interpolations, extrapolations, regressions, least squares approximations, linear approximations, non-linear approximations, Taylor series, power series, etc.). As an illustrative example of a relationship between an intensity value and a color temperature, the desired intensity value is converted to a desired intensity value in lumens. An exemplary conversion is provided below in EQN. 1.

$$\text{Lumens} = \text{Max Lumens} \times \left( \frac{\text{Actual Intensity}}{\text{Max Intensity}} \right)^x \quad \text{EQN. 1}$$

where the maximum intensity is the maximum intensity setting for the light fixture (e.g., 255 for an 8-bit input value), the actual intensity is the intensity value setting based on the input parameter, the maximum lumens is the maximum lumen setting for the light fixture, and the exponent, X, has a value that is based on a manner in which the intensity of the light fixture is dimmed.

The desired intensity value in lumens can then be correlated to an intensity value in volts. An exemplary conversion is provided below in EQN. 2.

$$\text{Volts} = \text{Max Volts} \times \left( \frac{\text{Actual Lumens}}{\text{Max Lumens}} \right)^y \quad \text{EQN. 2}$$

where the maximum volts is the maximum volt reading for the light fixture, the maximum lumens is the maximum lumen setting for the light fixture (e.g., 255 for an 8-bit input value), the actual lumens is the lumen setting calculated using EQN. 1, and the exponent, Y, has a value that is based on a relationship between lumens and volts for the light fixture 100.

The intensity value in volts is then converted to a color temperature. An exemplary conversion is provided below in EQN. 3.

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$$\text{Color Temperature} = \text{Max Color Temp} \times \left( \frac{\text{Actual Volts}}{\text{Max Volts}} \right)^Z \quad \text{EQN. 3}$$

where the maximum color temperature is a maximum color temperature setting for the light fixture or the maximum color temperature achievable by the light fixture. The maximum volts is the maximum volt reading for the light fixture, the actual volts is the volt setting calculated using EQN. 2, and the exponent, Z, has a value that is based a relationship between color temperature and volts for the light fixture **100**. The calculated color temperature can then be associated with, or approximated to, a color space coordinate (e.g., an x-y coordinate at  $(x_w, y_w)$ ) that lies on the Planckian locus and corresponds to the color temperature of an ideal black-body radiator. Each of the conversions shown in EQNS. 1-3 can be combined into a single conversion or relationship, or can be executed separately. The relationships between the intensity values and color temperature are then used to generate one or more color temperature transforms, as described below. In some implementations, the relationships between each of the intensity values and a color temperature are stored in memory. Additionally or alternatively, the color temperatures corresponding to particular intensity values are stored in memory. For example, depending on a desired resolution for the color temperature control, a predetermined number of color temperature values are stored in memory (e.g., 256 values, 65,536 values, etc.) that correspond to discrete intensity values or ranges of intensity values.

Returning to the process **400**, a color temperature transform is then selected and retrieved (i.e., from memory) based on the white point color temperature (step **430**), and the input parameters are used to determine a modified target color coordinate based on the color temperature transform (step **435**). In some implementations, the modified target color coordinate is different from the target color coordinate and the white point color coordinate (e.g., the modified target color coordinate does not substantially lie on the Planckian locus). In other implementations, the modified target color coordinate is the same as the white point color coordinate.

The color temperature transform is configured to generate a modified target color coordinate based on the desired target color. The color temperature transform is different than the standard color space conversion described above. As an illustrative example, given a particular target color, the standard color space conversion and the color temperature transform each generate a different color space coordinate. The color space coordinate generated using the known color space conversion substantially corresponds to the target color. However, the color space coordinate generated or determined using the color temperature transform is shifted within the color space in order to mimic the color temperature changes of an ideal black-body radiator.

The color temperature transforms are generated based on a selected color gamut (e.g., the RGB color gamut) that can be defined with respect to the CIE xyY color space **300**. For example, as described above, the user is able to select a desired target color based on any of a number of complex color control methodologies. The input values from the complex color control methodology are then associated with the RGB color gamut (e.g.,  $R_T, G_T, B_T$ ), which is represented by a triangle in the CIE xyY color space having a red coordinate  $(x_R, y_R)$ , a green coordinate  $(x_G, y_G)$ , and a blue coordinate  $(x_B, y_B)$ , which have predetermined values. The red coordinate, the green coordinate, and the blue coordinate correspond to the bounds of the RGB color gamut. The red coordinate, the green coordinate, and the blue coordinate are used to generate tristimulus values associated with each coordinate, as well as generate the color temperature transforms. For example, the tristimulus values for the red coordinate can be calculated using EQNS. 4-6 below.

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$$X_R = \frac{x_R}{y_R} \quad \text{EQN. 4}$$

$$Y_R = 1 \quad \text{EQN. 5}$$

$$Z_R = \frac{(1 - x_R - y_R)}{y_R} \quad \text{EQN. 6}$$

In a similar manner, the tristimulus values for the green coordinate can be calculated using EQNS. 7-9 below.

$$X_G = \frac{x_G}{y_G} \quad \text{EQN. 7}$$

$$Y_G = 1 \quad \text{EQN. 8}$$

$$Z_G = \frac{(1 - x_G - y_G)}{y_G} \quad \text{EQN. 9}$$

The tristimulus values for the blue coordinate can be calculated using EQNS. 10-12 below.

$$X_B = \frac{x_B}{y_B} \quad \text{EQN. 10}$$

$$Y_B = 1 \quad \text{EQN. 11}$$

$$Z_B = \frac{(1 - x_B - y_B)}{y_B} \quad \text{EQN. 12}$$

In some implementations, the tristimulus values for the red coordinate, the green coordinate, and the blue coordinate are calculated once and stored in memory. In other implementations, the tristimulus values are calculated continually, at predetermined intervals, or based on a user input.

After the white point color temperature and corresponding color space coordinate for the white point color temperature have been determined, as described above, tristimulus values for the white point color temperature can also be determined. For example, the tristimulus values for the white point color temperature can be calculated using EQNS. 13-15 below.

$$X_W = \frac{x_W}{y_W} \quad \text{EQN. 13}$$

$$Y_W = 1 \quad \text{EQN. 14}$$

$$Z_W = \frac{(1 - x_W - y_W)}{y_W} \quad \text{EQN. 15}$$

Using the tristimulus values for the red coordinate, the green coordinate, the blue coordinate, and the white point coordinate, a matrix of scale factors, S, can be calculated, as shown below in EQN. 16.

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$$\begin{bmatrix} S_R \\ S_G \\ S_B \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}^{-1} \begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} \quad \text{EQN. 16}$$

The matrix of scale factors, S, can then be used to calculate the tristimulus values associated with a modified target color, as shown below in EQN. 17.

$$\begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} = \begin{bmatrix} S_R X_R & S_G X_G & S_B X_B \\ S_R Y_R & S_G Y_G & S_B Y_B \\ S_R Z_R & S_G Z_G & S_B Z_B \end{bmatrix} \begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} \quad \text{EQN. 17}$$

where  $R_T$ ,  $G_T$ , and  $B_T$  are red, green, and blue values corresponding to the desired target color.

The x-y color coordinate (i.e., chromaticity) of the modified target color is then determined as a function of the tristimulus values  $X_M$ ,  $Y_M$ , and  $Z_M$ , as shown below in EQNS. 18-20.

$$x_M = \frac{X_M}{(X_M + Y_M + Z_M)} \quad \text{EQN. 18}$$

$$y_M = \frac{Y_M}{(X_M + Y_M + Z_M)} \quad \text{EQN. 19}$$

$$z_M = \frac{Z_M}{(X_M + Y_M + Z_M)} = 1 - x_M - y_M \quad \text{EQN. 20}$$

In some implementations, the relationships or transforms between the target color coordinate and the modified target color coordinate described above with respect to EQNS. 1-20 are combined into a single relationship to, for example, reduce processing time, processing requirements, and memory usage. In other implementations, the color temperature transforms corresponding to particular intensity values are stored in memory. For example, depending on a desired resolution for the color temperature control, a predetermined number of color temperature transforms are stored in memory (e.g., 256 transforms, 65,536 transforms, etc.) that correspond to discrete intensity values or ranges of intensity values. A color temperature transform can then be determined or retrieved from memory based on the intensity setting or stored color temperature value, and the x-y coordinate of the modified target color is determined based on the target color and the color temperature transform.

As described above, the target color coordinate determined using the color temperature transform is different from the target color coordinate that is determined using the standard conversion. As such, the target color coordinate determined using the color temperature transform is indicated as a “modified” target color coordinate. For descriptive purposes, the target color coordinate and the modified target color coordinate are each referred to as the target color coordinate with respect to the remainder of the process 400 (i.e., starting at step 420), because the remainder of the process 400 is substantially independent of the manner in which the target color coordinate was calculated. The target color coordinate is then stored to memory (step 420) and the process 400 proceeds to section AA shown in and described with respect to FIG. 5.

With reference to FIG. 5, a second variable, B, is initialized or set equal to one (step 440), and the light source variable, LS, is set equal to B (e.g., the first light source) (step 445). The

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light fixture 100, or a controller connected to the light fixture 100, uses stored spectral information for each of the light sources within the light fixture 100 (e.g., output intensities of the light sources with respect to wavelength) to determine a location for each light source within a particular color space (e.g., the CIE xyY color space 300). The spectral data for each of the light sources is sampled or gathered, for example, at the time of manufacture and stored in a memory. The spectral data is stored in a memory of the light fixture as a table or multiple tables of values. The values associated with the tables are accessed or retrieved to calculate an output of the light fixture (e.g., as a coordinate within a color space) without having to activate the light sources and use light sensors. The coordinates are also stored in memory, and can be accessed from memory for comparison to one or more additional calculated coordinates within a color space (e.g., the target color coordinate). In some implementations, the spectral data is gathered, stored, and utilized in a manner similar to that described in U.S. patent application Ser. No. 12/898,127, filed Oct. 5, 2010 and titled “SYSTEM AND METHOD FOR COLOR CREATION AND MATCHING,” the entire content of which is hereby incorporated by reference.

At step 450, the color space coordinate for the selected light source is retrieved from memory. The target color coordinate is also retrieved from memory (step 455). The distance between the target color coordinate and the color space coordinate for the first light source is then calculated (step 460). For example, if the target color coordinate is designated by an x-coordinate,  $x_T$ , and a y-coordinate,  $y_T$ , and the first light source is designated by an x-coordinate,  $x_1$ , and a y-coordinate,  $y_1$ , the distance,  $D_1$ , between the target color coordinate and the first light source coordinate can be calculated as shown below in EQN. 21. EQN. 21 can be used to calculate the distance between each of the light sources in the light fixture and the target color coordinate.

$$D_1 = \sqrt{(x_T - x_1)^2 + (y_T - y_1)^2} \quad \text{EQN. 21}$$

The calculated distance,  $D_1$ , for the first light source is then stored in memory (step 465). The selected light source corresponding to the second variable, B, is compared to the number of LEDs in the light fixture (step 470). If the selected light source is not the last light source in the light fixture, the second variable, B, is incremented by one (step 475) and the light source variable, LS, is reset to the new value of the second variable, B (step 445). If the selected light source is the last light source in the light fixture, the process 400 proceeds to section BB shown in and described with respect to FIG. 6.

The locations described herein generally relate to positions or coordinates within a color space that can be used to map colors in one, two, or three dimensional space, and allow for the consistent identification of colors. Implementations and constructions of the invention are described herein with respect to the CIE xyY color space, but other color spaces can also be used. The separations between the locations within the color space are described generally with respect to distances. However, the separations can also be based on, for example, ratios, products, sums, or differences between wavelengths, frequencies, intensities, polarizations, phases, color temperature, brightness, saturation, etc., and correspond generally to an intervening space or gap between points, values, quantities, objects, locations, and the like.

With reference to FIG. 6, a third variable, C, is initialized or set equal to one (step 480), and the light source variable, LS, is set equal to C (e.g., the first light source) (step 485). At step 490, the distance between the first light source and the target color coordinate is retrieved from memory. An intensity level



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for the first light source is then set based on the retrieved distance (step 495), and the intensity level is stored to memory (step 500). For example, the greater the distance between the light source color space coordinate and the target color coordinate, the lower the initial intensity value is set. As such, the distance between the light source color space coordinate, and the target color coordinate and the initial output intensity value for the light source are inversely related. In some implementations, the inverse relationship is a linear inverse relationship. In other implementations, the inverse relationship is an exponential, logarithmic, or the like. The light source intensities are, for example, one byte. Therefore, each light source intensity has a value between 0 (i.e., no output) and 255 (i.e., full-scale). After the initial output intensity value for light source is set, the selected light source corresponding to the third variable, C, is compared to the number of LEDs in the light fixture (step 505). If the selected light source is not the last light source in the light fixture, the third variable, C, is incremented by one (step 510) and the light source variable, LS, is reset to the new value of the third variable, C (step 485). If the selected light source is the last light source in the light fixture, the process 400 proceeds to section CC shown in and described with respect to FIG. 7.

At step 515 shown in FIG. 7, all of the light source intensity values are retrieved or accessed from memory. The stored LED data is also retrieved from memory (step 520) such that the total output of the light fixture (i.e., the output of each light source) can be calculated (step 525). For example, the output intensity of each light source with respect to wavelength is determined based on the initial output intensity values for each light source and the LED data. The output intensities of each light source are then combined to produce a set of data corresponding to the total output for the light fixture. The total output of the light fixture is then used to calculate a color space coordinate (step 530) for the total output of the light fixture based on the initial light source output intensity values and the color matching functions described above. The distance between the total light fixture output color space coordinate and the target color coordinate is then calculated (step 535) using, for example, EQN. 21 above. The distance calculated at step 535 is compared to a threshold value (step 540). The threshold value is, for example, a distance value, a percent-error value, a mean square error ("MSE"), or the like. If the distance is not less than or equal to the threshold value, the process 400 proceeds to section DD shown in and described with respect to FIG. 8. If the initial output intensity values for the light sources resulted in a light fixture output color space coordinate that was less than or equal to the threshold value, the light sources are driven or activated at the stored initial output intensity values (step 545).

With reference to FIG. 8 and step 550, a fourth variable, D, is initialized or set equal to one, and the light source variable, LS, is set equal to D (e.g., the first light source) (step 555). At step 560, a step size value is added to the output intensity value of the selected light source. The step size value is based on, for example, the separation or distance between the total light fixture output color space coordinate and the target color coordinate (e.g., the step size value is proportional to the separation between the total light fixture output color space coordinate and the target color coordinate). For example, if the distance between the total light fixture output color space coordinate and the target color coordinate is greater than or equal to one or more threshold values, the step size value is set proportionally large. If the distance between the total light fixture output color space coordinate and the target color coordinate is less than or equal to one or more threshold values, the step size value is set proportionally small. In some

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implementations, the step size value is a percentage value, an incremental intensity value, or the like. For example, if the step size value is 5%, the output intensity value for the light source is increased by 5%. Using the new output intensity value for the selected light source, the previously retrieved initial output intensity values for the remaining light sources (i.e., the un-modified initial output intensity values), and the previously retrieved LED data, the total output of the light fixture is recalculated (step 565). The color space coordinate for total light fixture output is also recalculated (step 570). The distance between the new color space coordinate for the total light fixture output and the target color coordinate is calculated (step 575), and the distance between the new color space coordinate for the total output and the target color coordinate is stored to memory (step 580). The output intensity value for the selected light source is then reset to the previous (i.e., un-modified) output intensity value (step 585). The selected light source corresponding to the fourth variable, D, is compared to the number of LEDs in the light fixture (step 590). If the selected light source is not the last light source in the light fixture, the fourth variable, D, is incremented by one (step 595) and the light source variable, LS, is reset to the new value of the fourth variable, D (step 555). The process 400 repeats steps 560-590 until the step size value has been added to each output intensity value for the light sources. If the selected light source is the last light source in the light fixture, the process 400 proceeds to section EE shown in and described with respect to FIG. 9.

At step 600 in FIG. 9, a fifth variable, E, is initialized or set equal to one, and the light source variable, LS, is set equal to the fifth variable, E (e.g., the first light source) (step 605). At step 610, a step size value is subtracted from the output intensity value of the selected light source. As described above, in some implementations, the step size value is based on the separation or distance between the total light fixture output color space coordinate and the target color coordinate, and the step size value is a percentage value, a decremental intensity value, or the like. For example, if the step size value is 5%, the output intensity value for the light source is decreased by 5%. Using the new output intensity value for the selected light source, the previously retrieved initial output intensity values for the remaining light sources, and the previously retrieved LED data, the total output of the light fixture is recalculated (step 615). The color space coordinate for total light fixture output is also recalculated (step 620). The distance between the new color space coordinate for the total light fixture output and the target color coordinate is calculated (step 625), and the distance between the new color space coordinate for the total output and the target color coordinate is stored in memory (step 630). The output intensity value for the selected light source is then reset to the previous output intensity value (step 635). The selected light source corresponding to the fifth variable, E, is compared to the number of LEDs in the light fixture (step 640). If the selected light source is not the last light source in the light fixture, the fifth variable, E, is incremented by one (step 645), and the light source variable, LS, is reset to the new value of the fifth variable, E (step 605). The process 400 repeats steps 610-640 until the step size value has been subtracted from each output intensity value for the light sources. If the selected light source is the last light source in the light fixture, the process 400 proceeds to section FF shown in and described with respect to FIG. 10. In some implementations, the addition and subtraction of the step size value to the output intensity of each light source are performed consecutively as opposed to adding the step size value to the output intensity of each LED source and then subtracting the step size value from each light source. In other

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implementations, subtraction of the step size value is performed before the addition of the step size value. Additionally or alternatively, the step size value varies between the addition and subtraction or from light source to light source based on, for example, initial intensity values, a calculated distance, or another feedback criterion.

With reference to FIG. 10, after the step size value has been added to and subtracted from the stored intensity values for each of the light sources, the stored distances associated with total light fixture output for each of the modified intensity values are retrieved or accessed from memory (step 650). For example, a seven light source light fixture has fourteen distance values stored in memory corresponding to the addition and subtraction of a step size value from the stored output intensity values for each light source. The retrieved distances are then compared to one another to determine the shortest distance (step 655). The shortest distance value corresponds to the set of output intensity values that resulted in the least amount of error (i.e., the addition or subtraction of the step size value that resulted in the most beneficial change in the output of the light fixture). After the shortest distance has been identified, the stored output intensity values are modified (step 660) to correspond to the output intensity values that produced the shortest distance. For example, the step size value is added to or subtracted from a single output intensity value.

After the step size value has been added to or subtracted from the output intensity value, the output intensity values of each of the light sources are normalized (step 665). For example, modifying the output intensity values as described above can result in each of the light sources having an output intensity value of less than 100.0%. In such an instance, the light source or light sources having the highest output intensity value are normalized to a 100.0% output intensity value. As an illustrative example, a light fixture including seven light sources has output intensity values for each of the light sources (following step 660) as shown below in Table #1. Because the green light source has the highest output intensity value (i.e., 80.0%), the output intensity value of the green light source is reset to an output intensity value of 100.0%. The increase in the output intensity value of the green light source is 25.0% based on the un-normalized output intensity value. As such, the output intensity values of each of the remaining light sources are also increased by 25.0% based on the un-normalized output intensity values. For example, the red light source has an un-normalized output intensity value of 40.0%. Increasing the output intensity by 25.0% results in a normalized output intensity value of 50.0%. The output intensity values of the light sources are normalized to ensure or at least approximate the combination of light source output intensity values that produces a maximum lumen output (i.e., a maximum luminous flux) for the light fixture. Although the step of normalizing the light source output intensity values is shown following step 660, the output intensity values can be normalized in the same or a similar manner later in the process 400 (e.g., following step 670, step 675, or step 685 (all described below)).

TABLE #1

Normalized Light Source Output Intensity Values		
Color	Un-Normalized Intensity	Normalized Intensity
Red	40.0%	50.0%
Red-Orange	50.0%	62.5%
Amber	60.0%	75.0%

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TABLE #1-continued

Normalized Light Source Output Intensity Values		
Color	Un-Normalized Intensity	Normalized Intensity
Green	80.0%	100.0%
Cyan	30.0%	37.5%
Blue	10.0%	12.5%
Indigo	20.0%	25.0%

The new output intensity values corresponding to that light sources are then stored in memory (step 670). The shortest distance is then compared to the threshold value (step 675). Because the normalization described above modified the output intensities of the light sources by the same amount, the ratios of the light source intensities remain the same. As such, the shortest distance that was determined at step 655 remains unchanged and does not need to be recalculated following the normalization of step 665. As described above, the threshold value is, for example, a distance value, a percent-error value, or the like. If the distance is not less than or equal to the threshold value, the process 400 proceeds to section GG shown in and described with respect to FIG. 8 where the new intensity values are retrieved from memory (step 680) and a step size value is again added to and subtracted from the new stored output intensity values. If the distance is less than the threshold value, the new light source intensity values are retrieved or accessed from memory (step 685), and the light sources are driven or activated at the stored output intensity values (step 690). Additionally, because the process 400 is capable of being executed by the light fixture itself and no powerful central computer is required, each light fixture in a system of light fixtures is capable of executing the process 400 in a parallel manner.

The process 400 can be performed or executed following, for example, receiving a set of input parameters, a determined change in the intensity value, a determined change in the white point, or the like. As such, additional modified target color points can be calculated based on a modification to the intensity value and without modification to the desired target color. For example, after a first modified target color coordinate has been identified, a change in the intensity value causes, among other things, a new white point color temperature and white point color coordinate to be identified, a new color temperature transformation to be selected, and a new modified target color coordinate to be calculated. Additionally or alternatively, the process 400 can be preformed each time a signal related to the input parameters is received (e.g., even if none of the values associated with those signals have changed).

Thus, the invention provides, among other things, systems and methods for controlling an output of a light fixture to mimic the color temperature changes of an ideal black-body radiator. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A method of controlling an output of a light fixture, the light fixture including four or more light sources, the method comprising:

receiving a first input parameter corresponding to a first color point within a color space;

receiving a second input parameter associated with a desired intensity for the first color point;

determining a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space;

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selecting a color temperature transform based on the white point;  
calculating a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point;  
determining a respective light source output value for each of the four or more light sources based on the third color point; and  
driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

2. The method of claim 1, wherein the relationship between the second input parameter and the color temperature of the black-body radiator includes a linear approximation of the color temperature of the black-body radiator.

3. The method of claim 1, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

4. The method of claim 1, further comprising  
receiving a third input parameter associated with a second desired intensity of the first color point; and  
determining a second white point based on a relationship between the third input parameter and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

5. The method of claim 4, further comprising  
selecting a second color temperature transform based on the second white point; and  
calculating a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

6. The method of claim 5, further comprising  
determining a second respective light source output value for each of the four or more light sources based on the fifth color point; and  
driving each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

7. The method of claim 5, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

8. A method of controlling an output of a light fixture, the light fixture including four or more light sources, the method comprising:  
receiving a set of input parameters, the set of input parameters corresponding to a first color point within a color space and an intensity for the first color point;  
determining a color temperature setting based on a relationship between the set of input parameters and the color temperature of a black-body radiator, the color temperature setting corresponding to a second color point within the color space;  
determining a color temperature transform based on the color temperature setting;  
calculating a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point

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being different than the first color point, and the third color point being different than the second color point;  
determining a respective light source output value for each of the four or more light sources based on the third color point; and  
driving each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

9. The method of claim 8, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

10. The method of claim 8, further comprising  
receiving a second set of input parameters corresponding to the first color point and a second intensity for the first color point; and  
determining a second white point based on a relationship between the second set of input parameters and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

11. The method of claim 10, further comprising  
selecting a second color temperature transform based on the second white point; and  
calculating a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

12. The method of claim 11, further comprising  
determining a second respective light source output value for each of the four or more light sources based on the fifth color point; and  
driving each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

13. The method of claim 11, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

14. A system for controlling the output of a light fixture, the system including:  
four or more light sources; and  
a controller configured to  
receive a first input parameter corresponding to a first color point within a color space,  
receive a second input parameter associated with a desired intensity for the first color point,  
determine a white point based on a relationship between the second input parameter and the color temperature of a black-body radiator, the white point corresponding to a second color point within the color space,  
select a color temperature transform based on the white point,  
calculate a third color point within the color space based on the color temperature transform, the color temperature transform defining a relationship between the first color point and the third color point, the third color point being different than the first color point, and the third color point being different than the second color point,  
determine a respective light source output value for each of the four or more light sources based on the third color point, and

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drive each of the four or more light sources at the respective light source output value to produce the output of the light fixture.

15. The system of claim 14, wherein the relationship between the second input parameter and the color temperature of the black-body radiator includes a linear approximation of the color temperature of the black-body radiator.

16. The system of claim 14, wherein the second color point substantially lies on the Planckian locus, the first color point does not substantially lie on the Planckian locus, and the third color point does not substantially lie on the Planckian locus.

17. The system of claim 14, wherein the controller is further configured to

receive a third input parameter associated with a second desired intensity of the first color point, and

determine a second white point based on a relationship between the third input parameter and the color temperature of the black-body radiator, the second white point corresponding to a fourth color point within the color space.

18. The system of claim 17, wherein the controller is further configured to

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select a second color temperature transform based on the second white point, and

calculate a fifth color point within the color space based on the second color temperature transform, the second color temperature transform defining a relationship between the third color point and the fifth color point, the fifth color point being different than the third color point, and the fifth color point being different than the fourth color point.

19. The system of claim 18, wherein the controller is further configured to

determine a second respective light source output value for each of the four or more light sources based on the fifth color point, and

drive each of the four or more light sources at the second respective light source output value to produce the output of the light fixture.

20. The system of claim 18, wherein the fourth color point substantially lies on the Planckian locus and the fifth color point does not substantially lie on the Planckian locus.

\* \* \* \* \*

## **Exhibit B**



(12) **United States Patent**  
**Florac et al.**

(10) **Patent No.:** **US 11,240,898 B2**  
(45) **Date of Patent:** **Feb. 1, 2022**

(54) **SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT**

(56) **References Cited**

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(71) Applicant: **Electronic Theatre Controls, Inc.**,  
Middleton, WI (US)  
(72) Inventors: **William R. Florac**, Verona, WI (US);  
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**James Uphoff**, Madison, WI (US)  
(73) Assignee: **Electronic Theatre Controls, Inc.**,  
Middleton, WI (US)

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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Search Report issued by the United Kingdom Intellectual Property Office for Application No. 2101900.5 dated Aug. 11, 2021 (3 pages).

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(21) Appl. No.: **17/173,286**

(22) Filed: **Feb. 11, 2021**

(65) **Prior Publication Data**

US 2021/0251064 A1 Aug. 12, 2021

*Primary Examiner* — Haissa Philogene

(74) *Attorney, Agent, or Firm* — Michael Best and Friedrich LLP

**Related U.S. Application Data**

(60) Provisional application No. 62/975,459, filed on Feb. 12, 2020.

(57) **ABSTRACT**

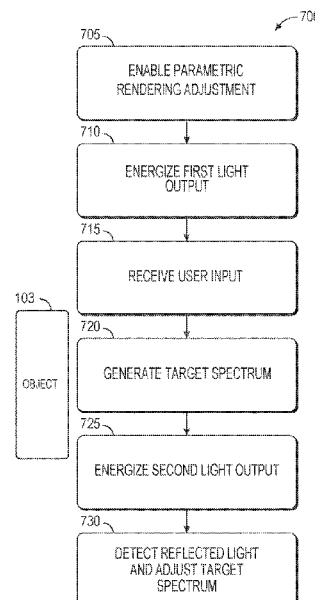
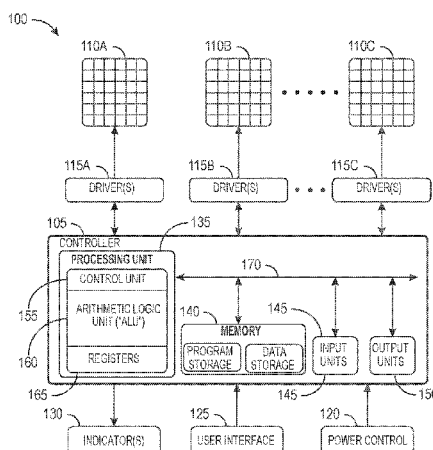
(51) **Int. Cl.**  
**H05B 45/20** (2020.01)  
**H05B 47/11** (2020.01)  
(52) **U.S. Cl.**  
CPC ..... **H05B 47/11** (2020.01); **H05B 45/20** (2020.01)

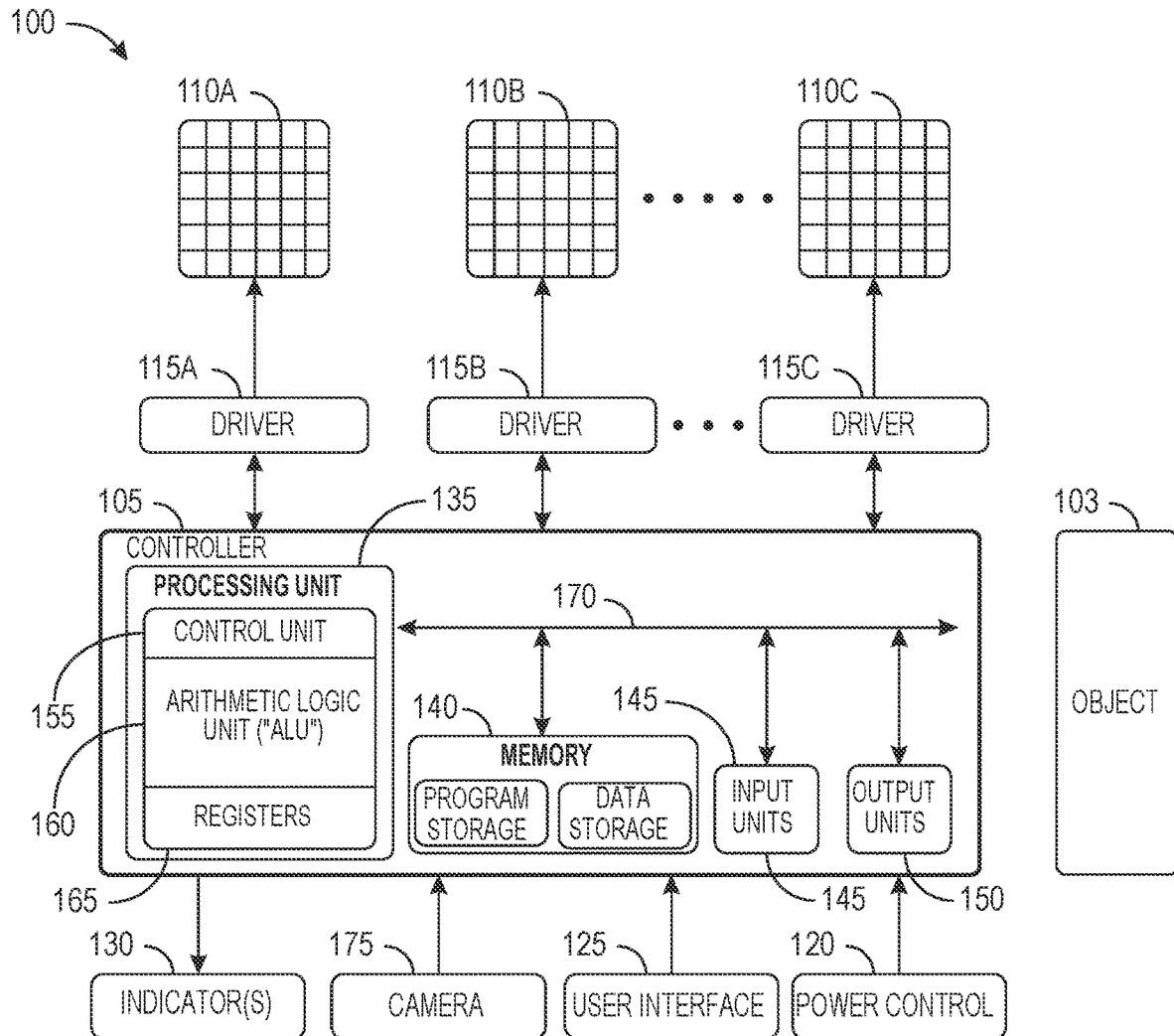
A method for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

(58) **Field of Classification Search**  
CPC ..... H05B 45/20; H05B 45/14; H05B 47/10;  
H05B 47/11; H05B 47/105; H05B  
47/115; Y02B 20/40

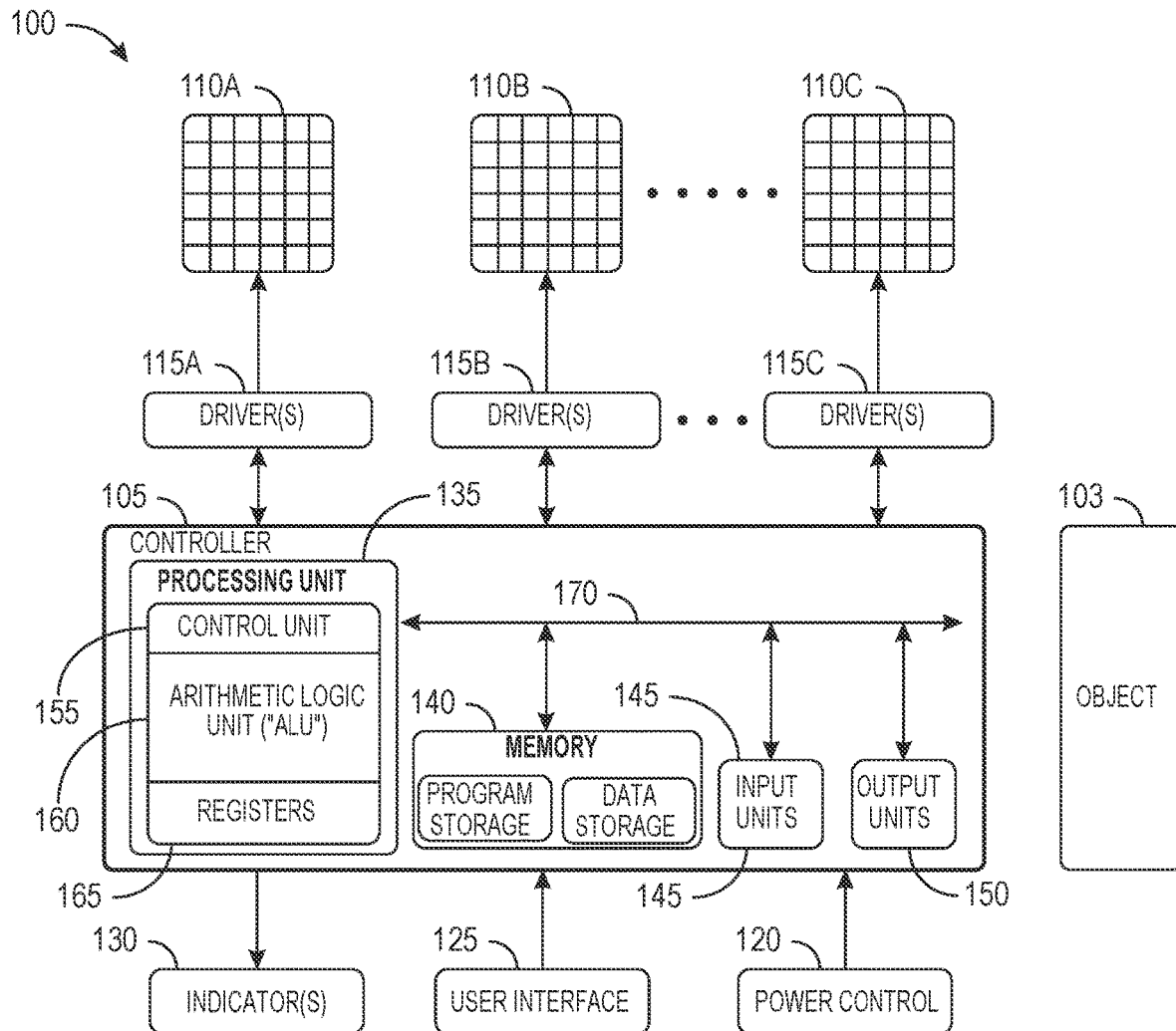
See application file for complete search history.

**20 Claims, 10 Drawing Sheets**

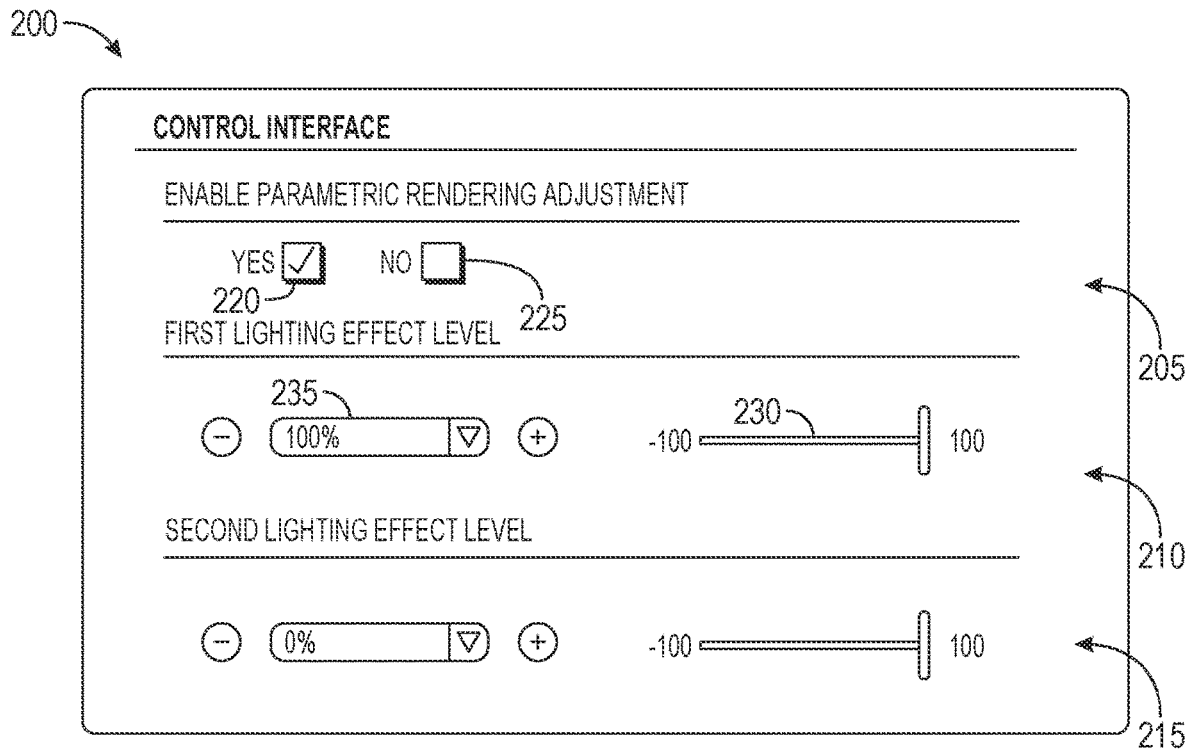




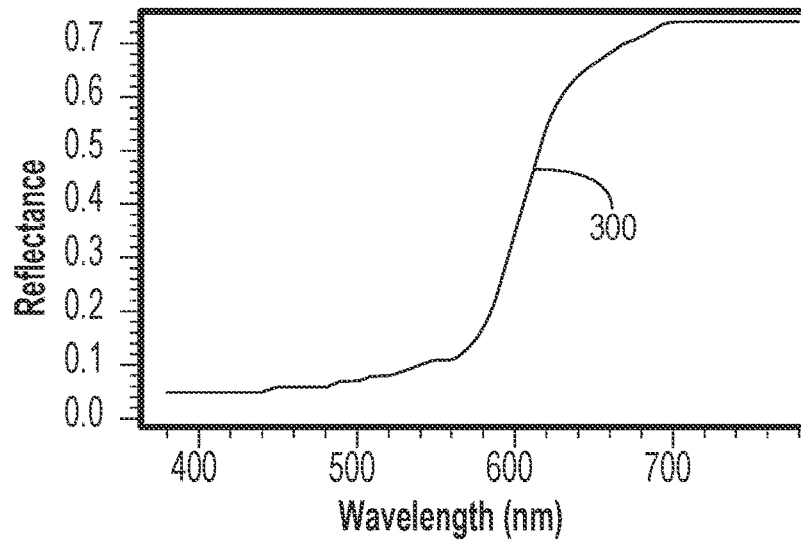
**FIG. 1**



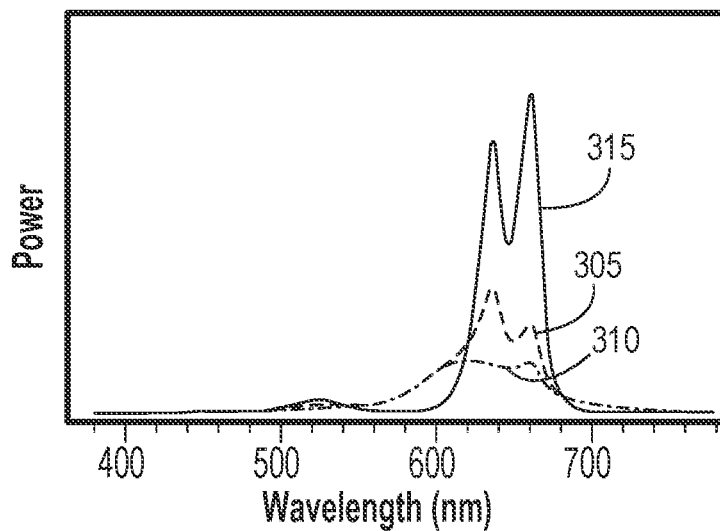
**FIG. 2**



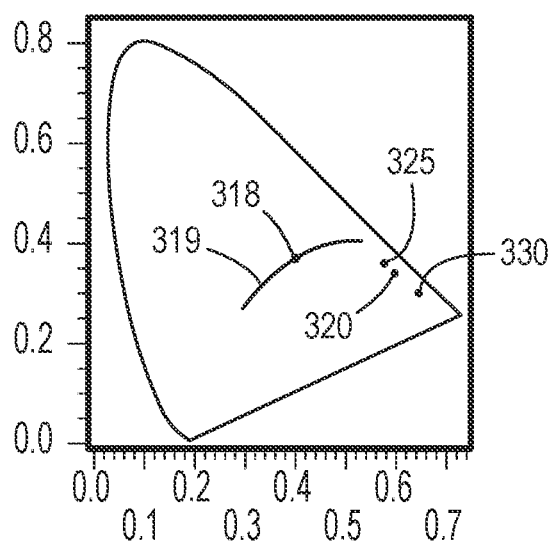
**FIG. 3**



**FIG. 4**



**FIG. 5**



**FIG. 6**

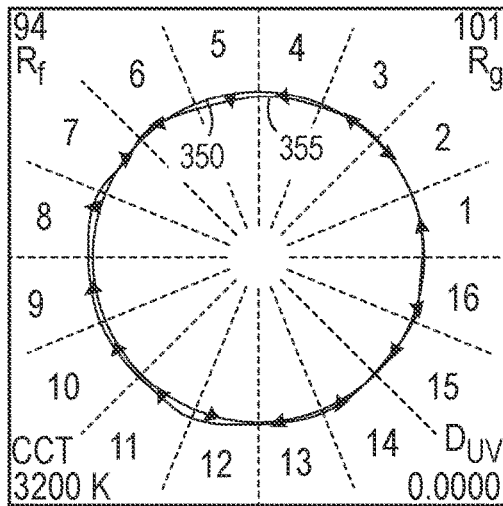


FIG. 7A

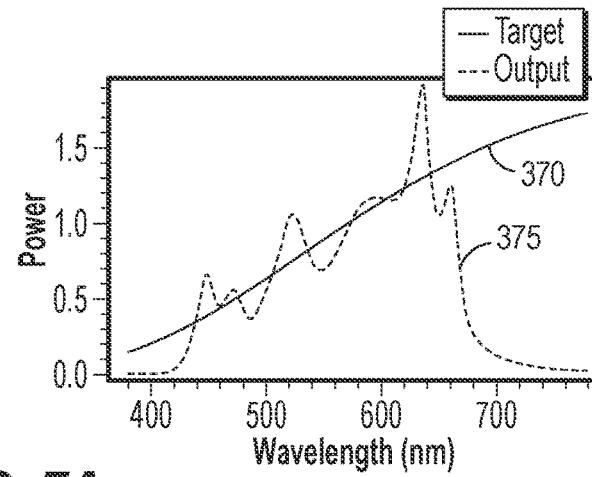


FIG. 8A

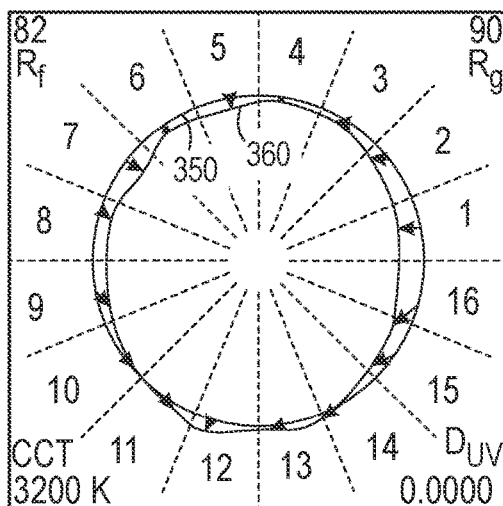


FIG. 7B

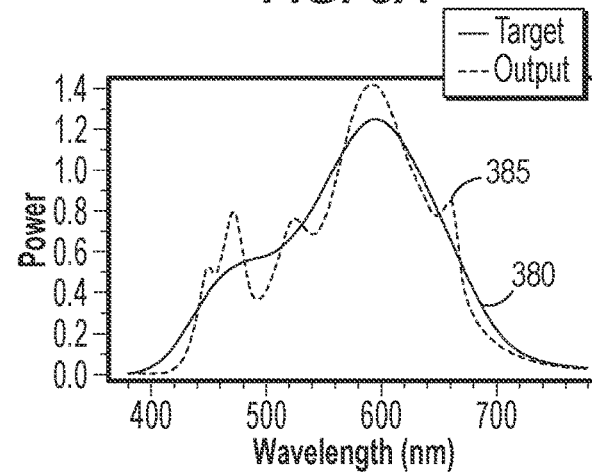


FIG. 8B

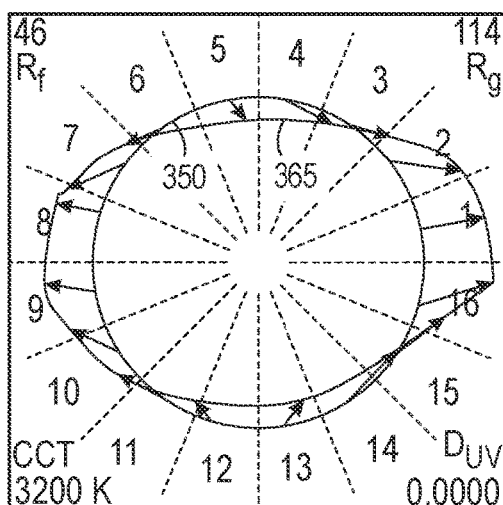


FIG. 7C

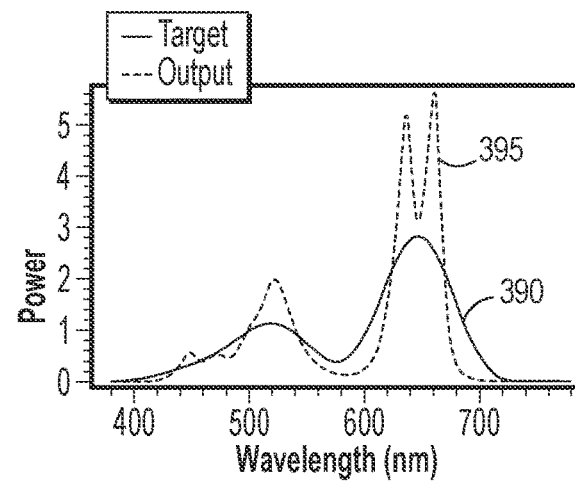


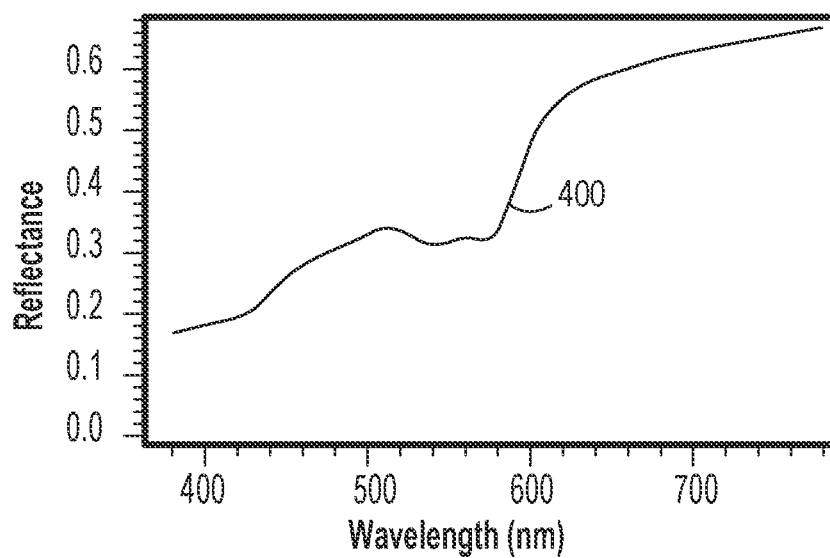
FIG. 8C

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**FIG. 9**

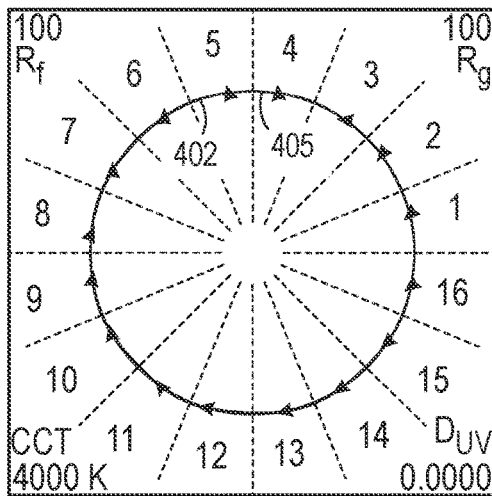


FIG. 10A

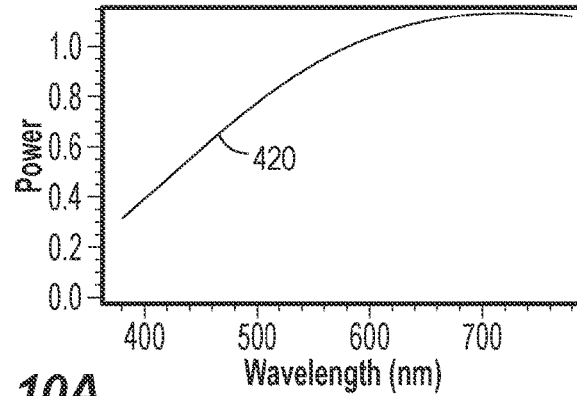


FIG. 11A

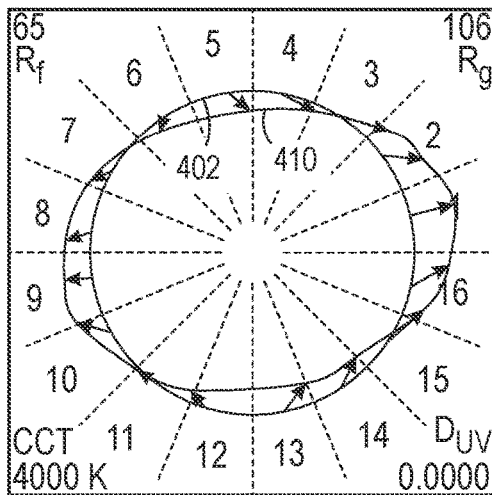


FIG. 10B

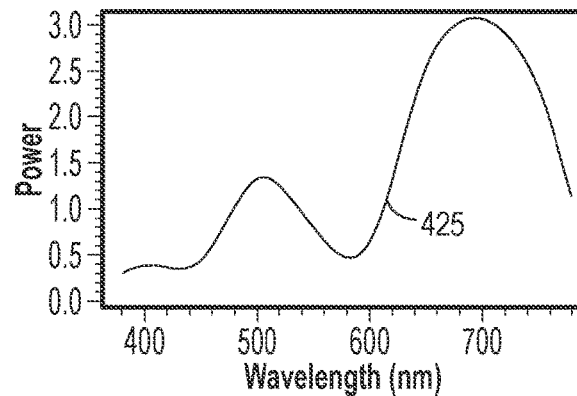


FIG. 11B

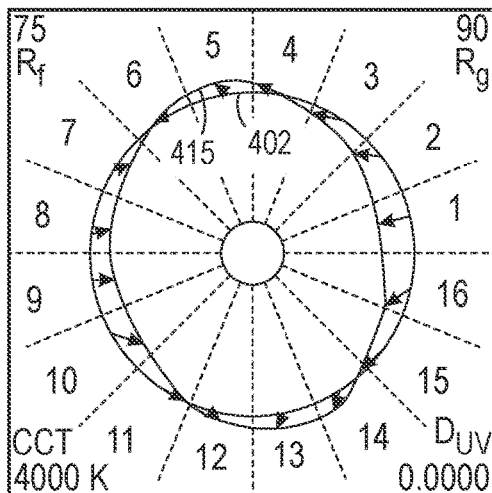


FIG. 10C

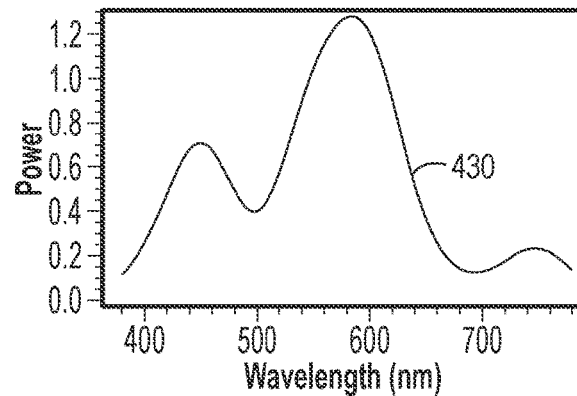


FIG. 11C



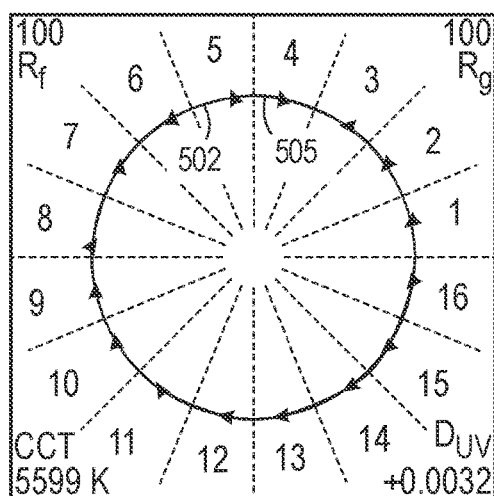


FIG. 12A

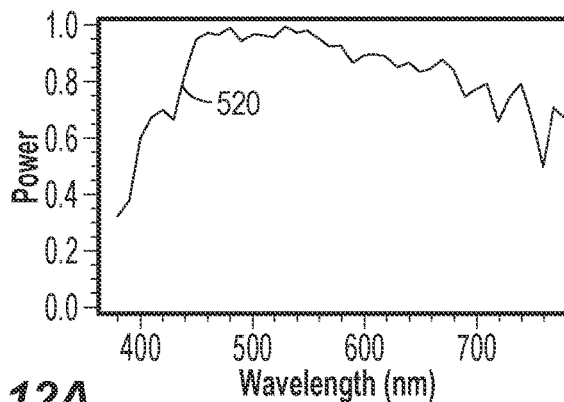


FIG. 13A

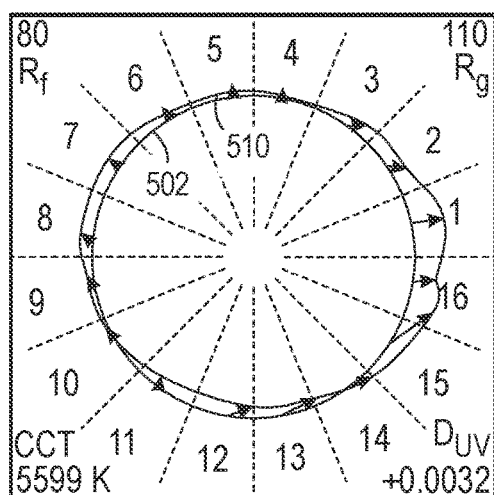


FIG. 12B

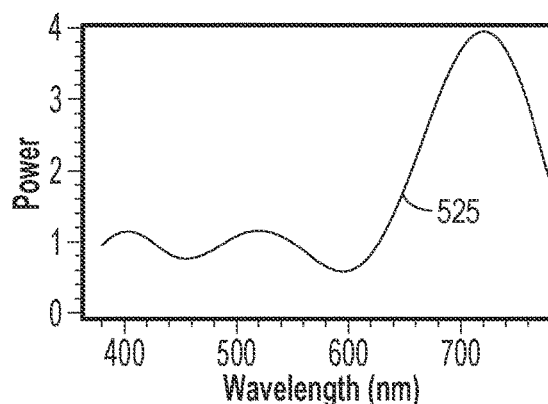


FIG. 13B

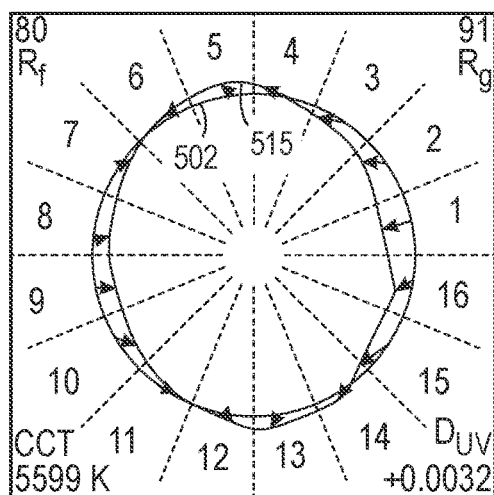


FIG. 12C

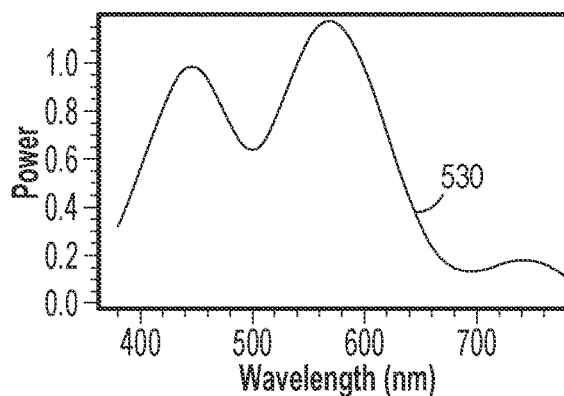


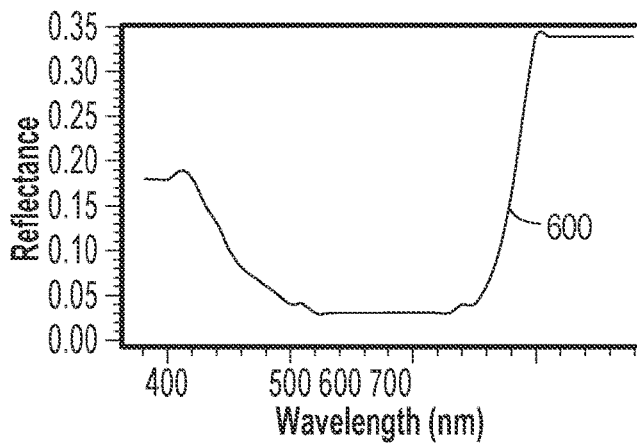
FIG. 13C

**U.S. Patent**

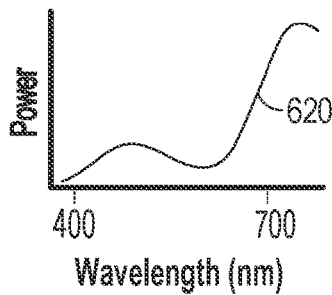
**Feb. 1, 2022**

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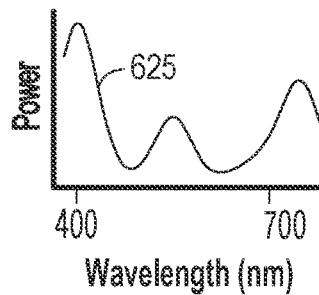
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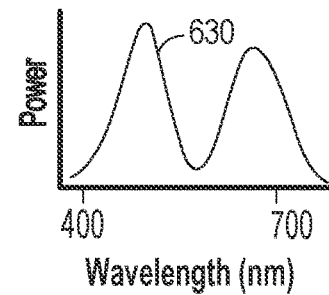
**FIG. 14**



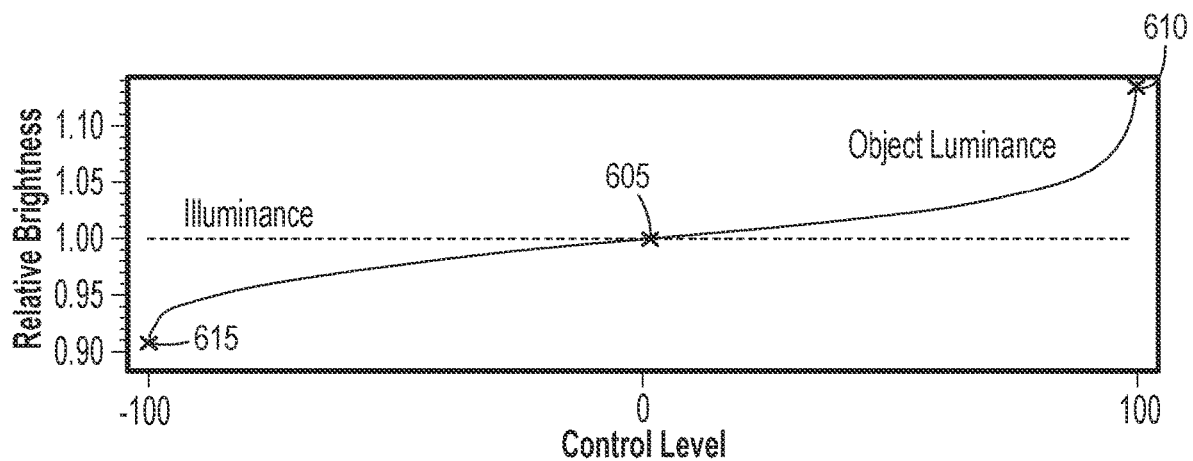
**FIG. 15A**



**FIG. 15B**



**FIG. 15C**



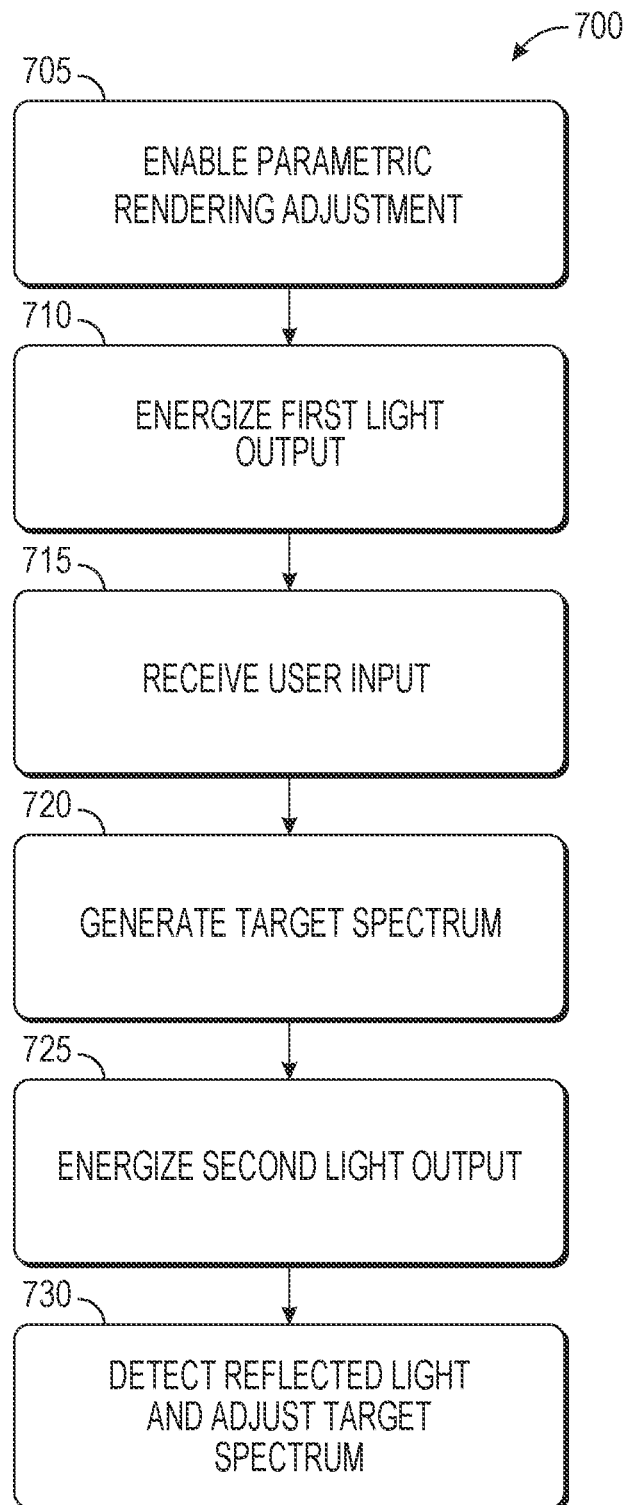
**FIG. 16**

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**FIG. 17**

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# SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/975,459, filed Feb. 12, 2020, the entire contents of which are hereby incorporated by reference herein.

## FIELD

Embodiments described herein relate to influencing the spectral content of a light output.

## BACKGROUND

Lighting systems used in architecture, theaters, concert stages, and other applications may be configured to control the light produced by a light source, such as a light fixture, luminaire, array of light emitting diodes, or other lighting device.

## SUMMARY

The lighting system may be controlled in various ways to produce a desired chromaticity (i.e., color) for the output light. Holding the chromaticity of the light output while adjusting the spectral content of the light output is called metameric control. For example, U.S. Pat. No. 8,723,450, incorporated herein by reference, discloses controlling the spectral content of the output of a light fixture by modifying the output intensity value of one or more of the light sources that make up the light fixture. For example, the user may adjust upwards the power output of a red light emitting diode (“LED”) within the light fixture. After modifying the output intensity values of individual emitters, a color control and matching technique is used to identify a new set of output intensity values for the remaining emitters that maintains the desired color output. The method of adjusting spectral content of a light output disclosed in U.S. Pat. No. 8,723,450 is specific to a given light fixture because the control adjusts the output of the specific light sources (e.g., individual LED) contained within the light fixture. However, different light fixtures have different light sources, so the method disclosed in U.S. Pat. No. 8,723,450 is not readily applicable or generic across different light fixtures. Finally, although the user is able to adjust the spectral content of the light output in the method disclosed in U.S. Pat. No. 8,723,450, the user is not provided control over or insight into how, for example, an object will appear when illuminated by the light output with the modified spectral content. In other words, the user is able to adjust the spectral content of the light output in U.S. Pat. No. 8,723,450 but does not have control over the lighting effect or effects (i.e., as perceived by a human observer or camera observer) created by the changing spectral content.

Embodiments described herein address this and other technical problems by analyzing aspects of perceived light to adjust the perceived appearance of the light output according to user specifications. The aspects of the perceived light controlled by embodiments described herein may include, for example, how the user perceives an object within the light output. In this way, the user alters the look and/or feel of the object according to how the user wants the

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object to appear. As a result, the user can alter how the object appears without altering the chromaticity of the light output. For example, the user may desire the object (e.g., human skin) to appear sickly under a metameric (constant-chromaticity) illuminant, or to appear brighter under a constant-power illuminant, or both.

Methods described herein provide for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

Lighting control systems described herein include one or more light fixtures, one or more driver circuits, a user interface, and a controller. The one or more driver circuits are configured to provide drive signals to the one or more light fixtures. The user interface is configured to receive an input related to a light output of the one or more light fixtures. The input is representative of an adjustment of a lighting effect. The controller is connected to the one or more driving circuits and the user interface. The controller includes a processor and a memory. The controller is configured to energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution, receive the input representative of the adjustment of the lighting effect, generate a target spectrum based on the input, and energize the one or more light fixtures to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

Controllers for controlling a light output of a light fixture described herein include a non-transitory computer readable medium and a processor. The controller includes computer executable instructions stored in the computer readable medium for controlling operation of the controller to energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receive an input representative of an adjustment of a lighting effect, generate a target spectrum based on the user input, and energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

It should be understood that the terms spectral match, spectrally matching, and the like (including similar terms with fixed or constant) refer to the application of an optimization procedure for spectrally matching the output composite light spectrum of the composite light source to a given target spectrum. It should be understood that the spectral match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints. Similarly, the terms chromaticity match, chromaticity matching, constant chromaticity, fixed chromaticity, and the like refer to the application of an optimization procedure for matching CIE chromaticity coordinates of the output composite light source spectrum to CIE chromaticity coordinates of a given target spectrum. It should be understood that the chromaticity match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints.

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Before any embodiments are explained in detail, it is to be understood that the embodiments are not limited in their application to the details of the configuration and arrangement of components set forth in the following description or illustrated in the accompanying drawings. The embodiments are capable of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

In addition, it should be understood that embodiments may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic-based aspects may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processing units, such as a microprocessor and/or application specific integrated circuits (“ASICs”). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components, may be utilized to implement the embodiments. For example, “servers” and “computing devices” described in the specification can include one or more processing units, one or more computer-readable medium modules, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

Other aspects of the embodiments will become apparent by consideration of the detailed description and accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a lighting control system.

FIG. 2 is a block diagram of a lighting control system according to another embodiment.

FIG. 3 illustrates a control interface for a lighting system.

FIG. 4 is a graph of the spectral reflectance function for an object.

FIG. 5 is a graph illustrating the spectral power distribution of light reflected off the object of FIG. 4 under a default condition, a positive hue shift condition, and a negative hue shift condition.

FIG. 6 is a CIE 1931 chromaticity diagram illustrating the chromaticity of the object of FIG. 4 under the default condition, the positive hue shift condition, and the negative hue shift condition of FIG. 5.

FIG. 7A is a TM-30 color vector graphic for the default condition of FIG. 5.

FIG. 7B is a TM-30 color vector graphic for the positive hue shift condition of FIG. 5.

FIG. 7C is a TM-30 color vector graphic for the negative hue shift condition of FIG. 5.

FIG. 8A is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the default condition of FIG. 5.

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FIG. 8B is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the positive hue shift condition of FIG. 5.

FIG. 8C is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the negative hue shift condition of FIG. 5.

FIG. 9 is a graph of the spectral reflectance function of an object.

FIG. 10A is a TM-30 color vector graphic for a default condition for the object of FIG. 9.

FIG. 10B is a TM-30 color vector graphic for a positive chroma shift condition for the object of FIG. 9.

FIG. 10C is a TM-30 color vector graphic for a negative chroma shift condition for the object of FIG. 9.

FIG. 11A is a graph illustrating a target output spectral power distribution for the default condition of FIG. 10A.

FIG. 11B is a graph illustrating a target output spectral power distribution for the positive chroma shift condition of FIG. 10B.

FIG. 11C is a graph illustrating a target output spectral power distribution for the negative chroma shift condition of FIG. 10C.

FIG. 12A is a TM-30 color vector graphic for a default condition for a 5600K illuminant.

FIG. 12B is a TM-30 color vector graphic for an over-saturated condition for the 5600K illuminant.

FIG. 12C is a TM-30 color vector graphic for an under-saturated condition for the 5600K illuminant.

FIG. 13A is a graph illustrating a target output spectral power distribution for the default condition of FIG. 12A.

FIG. 13B is a graph illustrating a target output spectral power distribution for the oversaturation condition of FIG. 12B.

FIG. 13C is a graph illustrating a target output spectral power distribution for the undersaturation condition of FIG. 12C.

FIG. 14 is a graph of the spectral reflectance function of an object.

FIG. 15A is a target output spectral power distribution for a non-white chromaticity at a default illuminance of the object of FIG. 14.

FIG. 15B is a target output spectral power distribution for the non-white chromaticity at an increased illuminance of the object of FIG. 14.

FIG. 15C is a target output spectral power distribution for the non-white chromaticity at a decreased illuminance of the object of FIG. 14.

FIG. 16 is a graph illustrating the relative brightness of the object of FIG. 14.

FIG. 17 is a method for controlling a light output for a lighting system.

#### DETAILED DESCRIPTION

FIGS. 1 and 2 illustrate a control system 100 that can be used in, for example, a theatre, a hall, an auditorium, a hotel, a cruise ship, or the like. In some embodiments, the control system 100 is disposed within a light fixture. In other embodiments, only a portion of the control system 100 is disposed in the light fixture. The control system 100 is configured to generate a light output and project that light output onto an object 103 according to specifications of a user for how the object 103 is to appear in the light output. The object 103 may be a human (e.g., skin), an inanimate object (e.g., fruit or fabric), a wall, or the like. Additionally, the light output may be projected onto a plurality of objects 103 (e.g., a class of objects). For descriptive purposes, light



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is generally described as being projected onto the object 103. However, in any instance where the object 103 is referenced, light can additionally be projected onto a plurality of objects 103 of the same or different classes of objects. The user specifications may alter the look and/or feel of the object 103 according to how the user wants the object to appear, which allows the user to alter how the object appears without altering the chromaticity of the light output.

The control system 100 includes a controller 105, a plurality of light modules or light arrays 110A-110C (e.g., light fixtures, color channels, etc.), a plurality of driver circuits 115A-115C, a power control circuit 120, an input mechanism 125, and one or more indicators 130. The controller 105 includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller 105 and/or the system 100. For example, the controller 105 includes, among other things, a processing unit 135 (e.g., a microprocessor, a microcontroller, an electronic controller, an electronic processor, or another suitable programmable device), a memory 140, input units 145, and output units 150. The processing unit 135 includes, among other things, a control unit 155, an arithmetic logic unit ("ALU") 160, and a plurality of registers 165 (shown as a group of registers in FIG. 1), and is implemented using a known computer architecture (e.g., a modified Harvard architecture, a von Neumann architecture, etc.). The processing unit 135, the memory 140, the input units 145, and the output units 150, as well as the various modules connected to the controller 105 are connected by one or more control and/or data buses (e.g., common bus 170). The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the embodiments described herein. The control and/or data buses are shown generally for illustrative purposes.

In some embodiments, the control system 100 also includes a camera 175 configured to detect the light from the modules 110A-110C reflected off of the object 103 (as shown in FIG. 1). In some embodiments, the camera 175 is a spectrometer, or another device specifically designed to detect a light spectrum. In other embodiments, the control system 100 does not include the camera 175 (as shown in FIG. 2). In these embodiments, the control system 100 operates in an open loop manner (i.e., without a closed-loop camera feedback system).

The memory 140 is a non-transitory computer readable medium and includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as a ROM, a RAM (e.g., DRAM, SDRAM, etc.), EEPROM, flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit 135 is connected to the memory 140 and executes software instructions that are capable of being stored in a RAM of the memory 140 (e.g., during execution), a ROM of the memory 140 (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the control system 100 can be stored in the memory 140 of the controller 105. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller 105 is configured to retrieve from the memory 140 and execute, among other things, instructions

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related to the control processes and methods described herein. In other embodiments, the controller 105 includes additional, fewer, or different components.

The user interface 125 is included to control the control system 100. The user interface 125 is operably coupled to the controller 105 to control, for example, the output of the light modules 110A-110C, and generate and provide control signals for the driver circuits 115A-115C. The user interface 125 can include any combination of digital and analog input devices to achieve a desired level of control for the control system 100. For example, the user interface 125 can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some embodiments, the user interface 125 is separated from the control system 100 (e.g., as a portable device communicatively connected to the controller 105).

The driver circuits 115A-115C include a first driver circuit 115A, a second driver circuit 115B, and a third driver circuit 115C that are operable to provide control signals to the light modules 110A-110C. For example, the first driver circuit 115A is connected to a first light module 110A for providing one or more drive signals to an array of (i.e., one or more) light sources of the first light module 110A. The second driver circuit 115B is connected to a second light module 110B for providing one or more drive signals to an array of (i.e., one or more) light sources on the second light module 110B. The third driver circuit 115C is connected to a third light module 110C for providing one or more drive signals to an array of (i.e., one or more) light sources on the third light module 110C. In some embodiments, each of the light modules 110A-110C corresponds to a color channel of a light. In other embodiments, each of the light modules 110A-110C corresponds to a separate light fixture.

The power control circuit 120 supplies a nominal AC or DC voltage to the control system 100. In some embodiments, the power control circuit 120 is powered by one or more batteries or battery packs. In other embodiments, the power control circuit 120 is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power control circuit 120 is also configured to supply lower voltages to operate circuits and components within the control system 100.

As illustrated in FIGS. 1 and 2, the controller 105 is connected to light modules 110A-110C. In some embodiments, each light module 110A-110C is a chip-on-board ("COB") light source. A three light module embodiment is illustrated for exemplary purposes only. In other embodiments, four or more light modules are used to further enhance the system 100's ability to produce visible light. Conversely, in other implementations, fewer than three light modules are used (i.e., one or two light modules). In some embodiments, the light modules 110A-110C are light emitting diode ("LED") light modules. In some embodiments, the light modules 110A-110C produce white light. In other embodiments, the light modules 110A-110C produce colored light (i.e., non-white light).

The control system 100 further includes a control interface 200 (see FIG. 3) for controlling a visual appearance of the light output light from the light modules 110A-110C that is, for example, reflected from the object 103. In some embodiments, the control interface 200 is included in the user interface 125. The control interface 200 is, for example, a graphical user interface ("GUI") that is displayed on a monitor or similar display. In some embodiments, the con-

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trol interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like.

The illustrated control interface **200** includes an optional enable parametric rendering adjustment section **205**, a first lighting effect level section **210**, and a second lighting effect level section **215**. The enable parametric rendering adjustment section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect parametric rendering adjustment (i.e., control based on visual appearance of the lighting effect).

The parametric rendering adjustment can use the first lighting effect level section **210** and/or the second lighting effect level section **215** to implement lighting effects that modify the appearance of light, for example, reflected off the object **103**. The first and second lighting effect level of the sections **210**, **215** may include control of quality, luminance, hue, power, color temperature, or the like. The first and second lighting effects are generic to any light fixture and allows the user to control effects to the best of the system's ability, regardless of what light fixture is used.

In some embodiments, the parametric rendering adjustment includes more than two lighting effect level sections. In the illustrated embodiment, each of the lighting effect level sections includes a maximum value and a minimum value. For the purposes of this embodiment, the maximum value is a value of positive 100 (e.g., oversaturation). The minimum value is a value of negative 100 (e.g., undersaturation). For example, the maximum undersaturation value is the inverse of the maximum oversaturation value. The first and second lighting effect level sections **210**, **215** each include a slider **230** and a drop-down menu **235**. The slider **230** ranges from negative 100 to positive 100 (e.g., from undersaturation to oversaturation). The drop-down menu **235** ranges from -100% to 100%. In other embodiments, the first and second lighting effect level sections **210** include different selection mechanisms. In conventional lighting control systems, the first and second lighting effects are not directly controllable along a continuum (i.e., negative 100 to positive 100). In this way, the control interface **200** permits the user to precisely control aspects of the output light that would not otherwise be directly adjustable and controllable by conventional controls, all while maintaining the same output chromaticity. Non-limiting examples of lighting effects to be controlled by the interface **200** are described in further detail herein.

With reference to FIGS. 4-8C, in one embodiment, the lighting effect controlled by the interface **200** is the hue shift of an object illuminated by the light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different colors and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. 4, a spectral reflectance function **300** of a first example object (e.g., a grapefruit) is illustrated. The spectral reflectance function **300** illustrates how incoming light will be reflected off the object—with longer wavelengths (e.g., greater than 600 nm) reflected more than shorter wavelengths. With the control interface **200**, the hue of the first example object may be controlled between a default condition, a positive hue shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative hue shift condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the color appearance of the first example object without changing the chromaticity of the output light. For each of these conditions, the resulting spectral power distribution of light

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reflected off the first example object (i.e., the grapefruit's rendered spectra) is illustrated in FIG. 5. Specifically, the rendered spectrum **305** is for the default condition, the rendered spectrum **310** is for the positive hue shift condition, and the rendered spectrum **315** for the negative hue shift condition.

With reference to FIG. 6, each of these rendered spectra **305**, **310**, **315** correspond to an object chromaticity **320**, **325**, **330** as illustrated in a CIE 1931 chromaticity diagram. More specifically, the first example object appears to an observer at a default chromaticity **320** with an output light chromaticity **318**. In the illustrated embodiment, the output light chromaticity **318** is on the Planckian locus **319** and is held constant. The first example object appears to an observer at a positive hue shift chromaticity **325** in the positive hue shift condition and at a negative hue shift chromaticity **330** in the negative hue shift condition. As such, the control interface **200** permits a user to adjust the chromaticity of the light reflected off of the first example object while maintaining the output light chromaticity constant.

With reference to FIGS. 7A-7C, color vector graphics are illustrated according to the TM-30 standard. In general, a color vector graphic shows how the color evaluation samples, representative of a wide range of objects, are likely to undergo either a saturation (chroma) shift, a hue shift, or both. The color vector graphic is divided into 16 equal sections with for, example, section 1 representative of red and section 9 representative of cyan. The reference illuminant is normalized to a reference circle **350** and the gamut of the light source is plotted relative to the circle as a distorted circle (e.g., **360** of FIG. 7B). Arrows that point radially into the reference circle **350** indicate areas of decreased saturation while areas that point radially out of the reference circle **350** indicate areas of increased saturation. Arrows that do not point directly to the center of the circle **350** or directly away from the center **350** of the circle are representing hue shift. In short, the color vector graphics can be used to illustrate how objects will appear in an output light relative to a reference light source (e.g., daylight).

With continued reference to FIGS. 7A-7C, the color vector graphics are illustrated for the default condition (FIG. 7A), the positive hue shift condition (FIG. 7B), and the negative hue shift condition (FIG. 7C). In FIG. 7A, the light source output gamut **355** closely tracks the reference circle **350** in the default condition. Attributes of the output light ( $R_p$ ,  $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. 7A. In FIG. 7B, the light source output gamut **360** is adjusted in the positive hue shift condition, and in FIG. 7C, the light source output gamut **365** is adjusted in the negative hue shift condition. The CCT value of 3200 K and  $D_{uv}$  of 0.0000 is held constant for FIGS. 7A-7C.

To achieve the default, positive hue shift, and negative hue shift conditions desired by the user, the controller **105** determines the corresponding target output light spectrums **370**, **380**, **390** illustrated in FIGS. 8A-8C. The target output light spectrums **370**, **380**, **390** correspond to the default, positive hue shift, and negative hue shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., **318**). In other words, there are numerous metamers for the target chromaticity (e.g., **318**) and the controller **105** selects the metamer that results in the hue shift condition desired by the user. The selection of the metamer for a desired hue shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not

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limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

With the target output light spectrums **370**, **380**, **390** determined, conventional spectral matching techniques (such as those disclosed in U.S. Pat. No. 6,683,423; incorporated herein) are utilized to determine how to drive the actual light emitters contained within a given fixture. In other words, the control system **100** determines an idealized target output spectrum for controlling the hue shift of the first example object. As one example, the actual output spectral power distribution achieved for an example light fixture containing eight primary emitters is illustrated as output spectrum distributions **375**, **385**, **395** on FIGS. **8A-8C**. In other words, the output spectrum distributions **375**, **385**, **395** illustrate a given light fixture's best ability to match the target output light spectrums **370**, **380**, **390**.

In summary, FIGS. **4-8C** illustrate the implementation of control for hue shift of a first example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the light that is reflected off of the first example object (i.e., change in reflected light chromaticities **320**, **325**, **330**), while holding the output light chromaticity constant (e.g., chromaticity **318**). The hue shift of the first example object is not directly adjustable with conventional controls.

With reference to FIGS. **9-11C**, in another embodiment, the lighting effect controlled by the interface **200** is the chroma shift of an object illuminated by the light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different saturations and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **9**, a spectral reflectance function **400** of a second example object (e.g., one example of human skin) is illustrated. The spectral reflectance function **400** illustrates how incoming light will be reflected off the second example object. With the control interface **200**, the chroma (i.e., saturation) of the second example object may be controlled between a default condition, a positive chroma shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative chroma shift condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the saturation appearance of the second example object without changing the chromaticity of the output light. As such, the  $R_g$  value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **10A-10C**, the color vector graphics are illustrated for the default condition (FIG. **10A**), the positive chroma shift condition (FIG. **10B**), and the negative chroma shift condition (FIG. **10C**). In FIG. **10A**, the light source output gamut **405** closely tracks the reference circle **402** in the default condition and the  $R_g$  value is 100. Attributes of the output light ( $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. **10A**. In FIG. **10B**, the light source output gamut **410** is adjusted in the positive chroma shift condition with a  $R_g$  value of 106, and in FIG. **10C**, the light source output gamut **415** is adjusted in the negative chroma shift condition with a  $R_g$  value of 90. The CCT value of 4000 K and  $D_{uv}$  of 0.0000 is held constant for FIGS. **10A-10C**.

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With reference to FIGS. **11A-11C**, for each of the desired chroma-shifts in the second example object there is a corresponding output target spectrum power distribution **420**, **425**, **430**. The target output light spectrums **420**, **425**, **430** correspond to the default, positive chroma shift, and negative chroma shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=4000 K and  $D_{uv}$ =0.0000). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the chroma shift condition for the second example object desired by the user. The selection of the metamer for a desired chroma shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **420**, **425**, **430** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used. Conventional target spectral matching techniques may be utilized to drive emitters in a given light fixture in order to approximate the target.

In summary, FIGS. **9-11C** illustrate the implementation of control for chroma shift of a second example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the saturation of the light reflected off of the second example object, while holding the output light chromaticity constant. The chroma shift of the second example object is not directly adjustable with conventional controls.

With reference to FIGS. **12A-13C**, in another embodiment, the lighting effect controlled by the interface **200** is the generalized saturation appearance of object(s) (i.e.,  $R_g$  value) of an approximately 5600 K light output of the light arrays **110A-110C**. With the control interface **200**, the generalized saturation may be controlled between a default condition, a generalized oversaturation condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a generalized undersaturation condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the generalized saturation appearance of object(s) without changing the chromaticity of the output light. As such, the  $R_g$  value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **12A-12C**, the color vector graphics are illustrated for the default condition (FIG. **12A**), the generalized oversaturation condition (FIG. **12B**), and the generalized undersaturation condition (FIG. **12C**). In FIG. **12A**, the light source output gamut **505** closely tracks the reference circle **502** in the default condition and the  $R_g$  value is 100. Attributes of the output light ( $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. **12A**. In FIG. **12B**, the light source output gamut **510** is adjusted in the generalized oversaturation condition with a  $R_g$  value of 110, and in FIG. **12C**, the light source output gamut **515** is adjusted in the generalized undersaturation condition with a  $R_g$  value of 91. The CCT value of 5599 K and  $D_{uv}$  of 0.0032 is held constant for FIGS. **12A-12C**.

With reference to FIGS. **13A-13C**, for each of the desired generalized saturation levels there is a corresponding output



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target spectrum power distribution **520, 525, 530**. The target output light spectrums **520, 525, 530** correspond to the default, oversaturated, and undersaturated conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=5599 K and  $D_{uv}=0.0032$ ). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the generalized saturation level desired by the user. The selection of the metamer for a desired saturation level may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **520, 525, 530** are generalized targets (similar to the target spectrum **370, 380, 390**) that are applicable to any type of light fixture being used.

In summary, FIGS. **12A-13C** illustrate the implementation of control for generalized saturation appearance of object(s) in an approximately 5600K illuminant (i.e., an example light effect level), while holding the output light chromaticity constant. The generalized saturation of a 5600K illuminant is not directly adjustable with conventional controls.

With reference to FIGS. **14-16**, in another embodiment, the lighting effect controlled by the interface **200** is the relative luminance of an object illuminated by a non-white light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be brighter or darker and can be adjusted by a user while holding the output light chromaticity constant at a non-white color and equal luminous flux.

With reference to FIG. **14**, a spectral reflectance function **600** of a third example object (e.g., a purple scarf) is illustrated. The spectral reflectance function **600** illustrates how incoming light will be reflected off the third example object. With the control interface **200**, the luminance (i.e., brightness) of the third example object may be controlled between a default condition (point **605** in FIG. **16**), an increased relative luminance condition (point **610** in FIG. **16**) (e.g., +100 adjustment of the first lighting effect level section **210**), and a decreased relative luminance condition (point **615** in FIG. **16**) (e.g., -100 adjustment of the first lighting effect level section **210**). The minimum (e.g., -100 from the interface **200** of FIG. **3**) and maximum (e.g., +100 from the interface **200** of FIG. **3**) are defined as the extremes of the lighting effect adjustment. The changes that occur to the target output spectrum between the spectrums **625, 630** for the minimum and maximum control levels, respectively, can then be mapped (e.g., linearly) to produce a target spectrum for control values between -100 and 100 for a controllable lighting effect. In other words, the control interface **200** is utilized by a user to control the luminance of the third example object without changing the chromaticity of the output light—which in this example is a blue output light. The brightness of the third example object is being adjusted relative to the rest of the scene illuminated, since the luminous flux of the output light is held constant.

With reference to FIGS. **15A-15C**, for each of the desired relative brightnesses of the third example object there is a corresponding output target spectrum power distribution

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**620, 625, 630**. The target output light spectrums **620, 625, 630** correspond to the default, increased relative brightness, and decreased relative brightness conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., blue, or "steel blue"). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the relative brightness condition for the third example object desired by the user. The selection of the metamer for a desired relative luminance may be preprogrammed into the memory **140** as a look-up table, for example. The target output light spectrums **620, 625, 630** are generalized targets (similar to the target spectrums **370, 380, 390**) that are applicable to any type of light fixture being used.

Although the described embodiment uses a look-up table to calculate a metamer, in other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

In summary, FIGS. **14-16** illustrate the implementation of control for relative brightness of a third example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the luminance of the light reflected off of the third example object relative to its surroundings, while holding the output light chromaticity constant at a non-white color and equal luminous flux. The relative luminance of the third example object illuminated by non-white light is not directly adjustable with conventional controls.

FIG. **17** illustrates a method **700** for using the control system **100** to adjust a lighting effect of the output light from light arrays **110A-110C**. Various steps described herein with respect to the process **700** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial manner of execution.

In some embodiments, the user enables the parametric rendering adjustment and alters the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200** (see FIG. **3**) to control the visual appearance of light on the object **103** (STEP **705**). In other embodiments, enabling parametric rendering adjustment is not specifically required. Before any adjustments are made, the method **700** includes energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution (STEP **710**). In other words, the light fixture generates a default light output. The controller **105** receives signals related to a user input that is representative of a desired adjustment of a lighting effect (STEP **715**). The desired adjustment of a lighting effect may include adjustment of the Illumination Engineering Society ("IES") Technical Memorandum 30 ("TM-30")  $R_g$  value of the light output; adjustment of a hue shift in an object illuminated by the light output; or adjustment of a chroma shift in an object illuminated by the light output. In other embodiments, the desired adjustment of a lighting effect may include adjustment of one or more parameters or metrics of a light output including but not limited to; Television Lighting Consistency Index ("TLCT"); Color Rendering Index ("CRI")  $R_a$ ; CRI  $R_9$ ; Spectral Similarity Index ("SSI"); TM-30  $R_p$ ; TM-30  $R_g$ ; TM-30  $R_{cs,h1}$ ; TB-30  $R_{f,h1}$ ; TM-30 Annex E's PVF (Preference, Vividness, Fidelity) values; Color Quality

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Scale ("CQS"); Pigment/dye/colorant alignment; Skin tone quality; Vibrance/richness; Increase or decrease in fluorescence or excitation of optical brighteners; generalized Cool/Warm appearance shift; Light source selection (e.g., tungsten 3200K vs HID 3200K vs fluorescent 3200K). Such adjustments may be applied independently or simultaneously in any combination of multiple parameters. In other embodiments, the desired adjustment of a lighting effect includes adjustment of a relative luminance of an object illuminated by the light output. In a further embodiment the desired adjustment of a lighting effect is to adjust skin tone rendition by suppressing or enhancing the cyan wavelengths. This adjustment, while maintaining a chromaticity match or constant chromaticity, provides the user the ability to tune the appearance of skin tones both to the eye and to a camera.

The method 700 further includes generating a target output light spectrum based on the user input received (STEP 720). In some embodiments, the target spectrum is retrieved from a look-up table stored in the memory 140. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The method 700 includes energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution (STEP 725). The second spectral power distribution approximates or matches the target spectrum and will depend on the type of light fixture utilized to create the target spectrum.

The inputted first and/or second lighting effect levels 210, 215 are used to modify a spectrum of light produced by the light modules 110A-110C. If the appearance of the object 103 is not satisfactory, the user can modify the first lighting effect level 210 and/or the second lighting effect level 215 on the control interface 200. In this way, the control is open-loop and based on user observations and adjustments. As such, the controller 105 is configured to dynamically alter the light output to achieve a desired visual appearance of the object 103, for example. In some embodiments, the light projected onto the object 103 can be white light or colored light (i.e., light other than white light), as shown in FIGS. 14-16.

In some embodiments, the camera 175 can be used to detect a reflectance of the light off of the object 103 (STEP 730). Based on the reflectance of light off of the object 103, as detected by the camera 175, further adjustments to the target output light spectrum may be made. In this sense, the control may provide a closed-loop system that detects and measures the lighting effect being adjusted. In some embodiments, STEP 730 is not included.

Thus, embodiments described herein provide, among other things, systems, methods, and devices for controlling a light output based on a visual appearance of one or more objects. Various features and advantages are set forth in the following claims.

What is claimed is:

1. A method for control of a light fixture, the method comprising:  
energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;

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receiving a user input representative of a desired adjustment of a lighting effect;

generating a target spectrum based on the user input; and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

2. The method of claim 1, wherein the lighting effect is the TM-30  $R_g$  value of the light output.

3. The method of claim 1, wherein the lighting effect is a hue shift of the light reflected by an object illuminated by the light output.

4. The method of claim 1, wherein the lighting effect is a chroma shift of the light reflected by an object illuminated by the light output.

5. The method of claim 1, wherein the lighting effect is a Television Lighting Consistency Index ("TLCI") value of the light output.

6. The method of claim 1, wherein the lighting effect is a Color Rendering Index ("CRI")  $R_a$  value of the light output.

7. The method of claim 1, wherein the lighting effect is a Spectral Similarity Index ("SSI") value of the light output.

8. The method of claim 1, wherein the lighting effect is the relative luminance of an object illuminated by the light output.

9. The method of claim 1, wherein the first light has a first lumen output and the second light has a second lumen output equal to the first lumen output.

10. The method of claim 1, wherein the first chromaticity is matched for a human eye observer.

11. The method of claim 1, wherein the first chromaticity is matched for a camera observer.

12. The method of claim 1, further including detecting reflected light off an object positioned in the second light output with a camera and adjusting the target spectrum based on the detected reflected light.

13. The method of claim 1, wherein the first chromaticity is non-white color.

14. The method of claim 1, wherein generating the target spectrum based on the user input includes retrieving the target spectrum from a table stored in a memory.

15. The method of claim 1, wherein the lighting effect is the TM-30  $R_f$  value of the light output.

16. The method of claim 1, wherein the lighting effect is the TM-30  $R_{cs,h1}$  value of the light output.

17. The method of claim 1, wherein the lighting effect is the TM-30  $R_{f,h1}$  value of the light output.

18. A lighting control system comprising:

one or more light fixtures;

one or more driver circuits configured to provide drive signals to the one or more light fixtures;

a user interface configured to receive an input related to a light output of the one or more light fixtures, the input being representative of an adjustment of a lighting effect; and

a controller connected to the one or more driving circuits and the user interface, the controller including a processor and a memory, the controller configured to:

energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution,

receive the input representative of the adjustment of the lighting effect,

generate a target spectrum based on the input, and energize the one or more light fixtures to produce a second light output with the first chromaticity and a

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second spectral power distribution, the second power distribution approximates the target spectrum.

19. The lighting control system of claim 18, wherein the first chromaticity is a non-white color.

20. A controller for controlling a light output of a light fixture, the controller including a non-transitory computer readable medium and a processor, the controller including computer executable instructions stored in the computer readable medium for controlling operation of the controller to:

energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution;

receive an input representative of an adjustment of a lighting effect;

generate a target spectrum based on the user input; and

energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

\* \* \* \* \*

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## Exhibit C

(12) **United States Patent**  
**Florac et al.**

(10) **Patent No.:** **US 11,849,519 B2**  
(45) **Date of Patent:** **\*Dec. 19, 2023**

(54) **SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 42 days.

This patent is subject to a terminal disclaimer.

(52) **U.S. Cl.**

CPC ..... **H05B 47/11** (2020.01); **H05B 45/20** (2020.01); **H05B 45/22** (2020.01); **H05B 47/125** (2020.01); **H05B 47/14** (2020.01)

(58) **Field of Classification Search**

CPC ..... **H05B 47/11**; **H05B 47/14**; **H05B 47/125**; **H05B 45/20**; **H05B 45/22**; **H05B 39/04**; **Y02B 20/40**

See application file for complete search history.

(56)

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(21) Appl. No.: **17/583,765**

(22) Filed: **Jan. 25, 2022**

(65) **Prior Publication Data**

US 2022/0151044 A1 May 12, 2022

**Related U.S. Application Data**

(63) Continuation of application No. 17/173,286, filed on Feb. 11, 2021, now Pat. No. 11,240,898.

(60) Provisional application No. 62/975,459, filed on Feb. 12, 2020.

(51) **Int. Cl.**

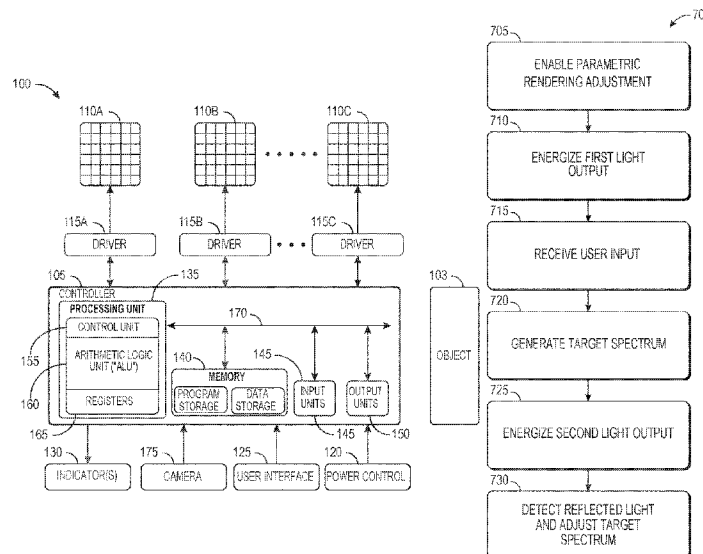
**H05B 47/11** (2020.01)  
**H05B 45/20** (2020.01)  
**H05B 47/125** (2020.01)  
**H05B 45/22** (2020.01)  
**H05B 47/14** (2020.01)

(57)

**ABSTRACT**

A method for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

**20 Claims, 10 Drawing Sheets**



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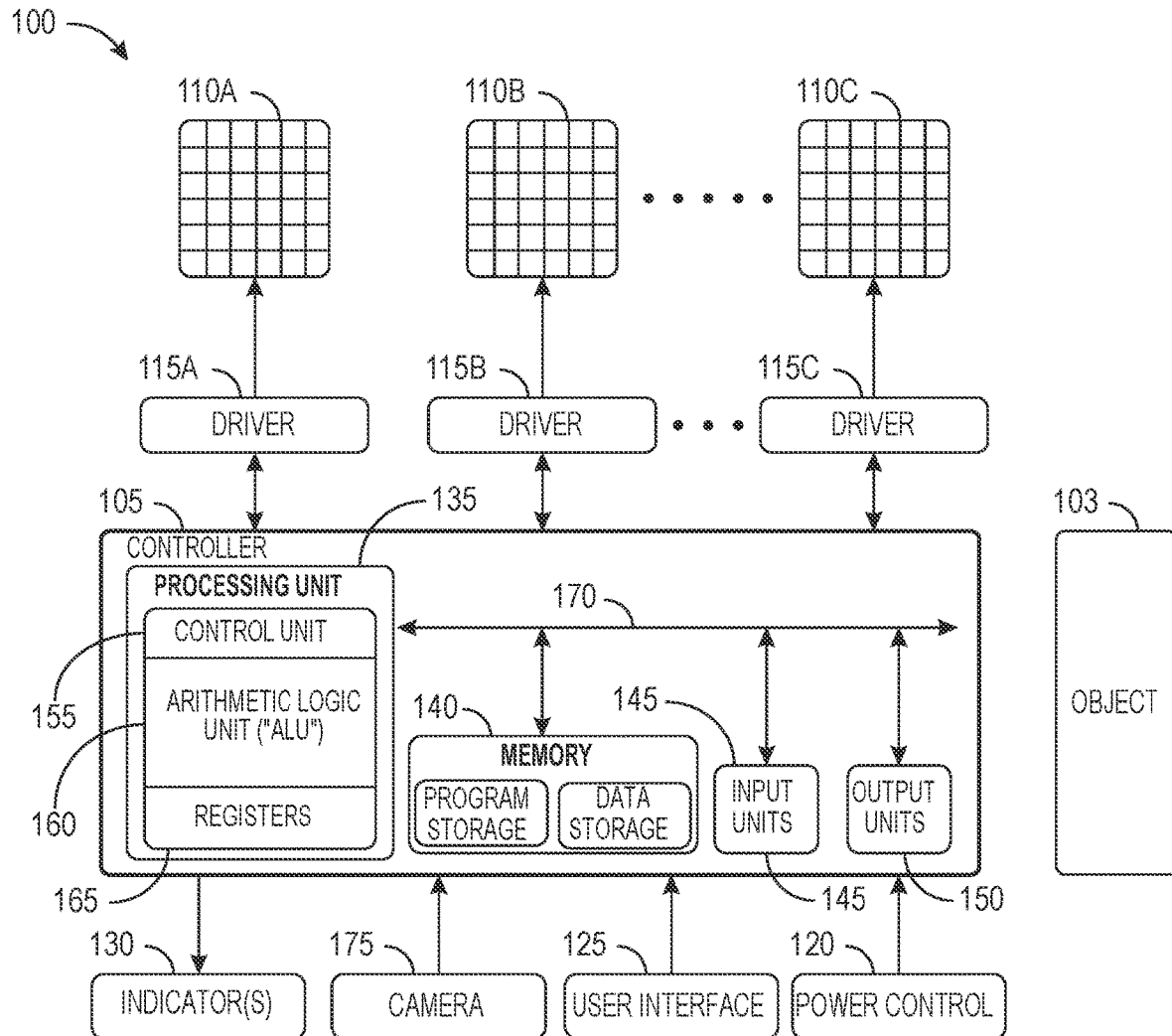
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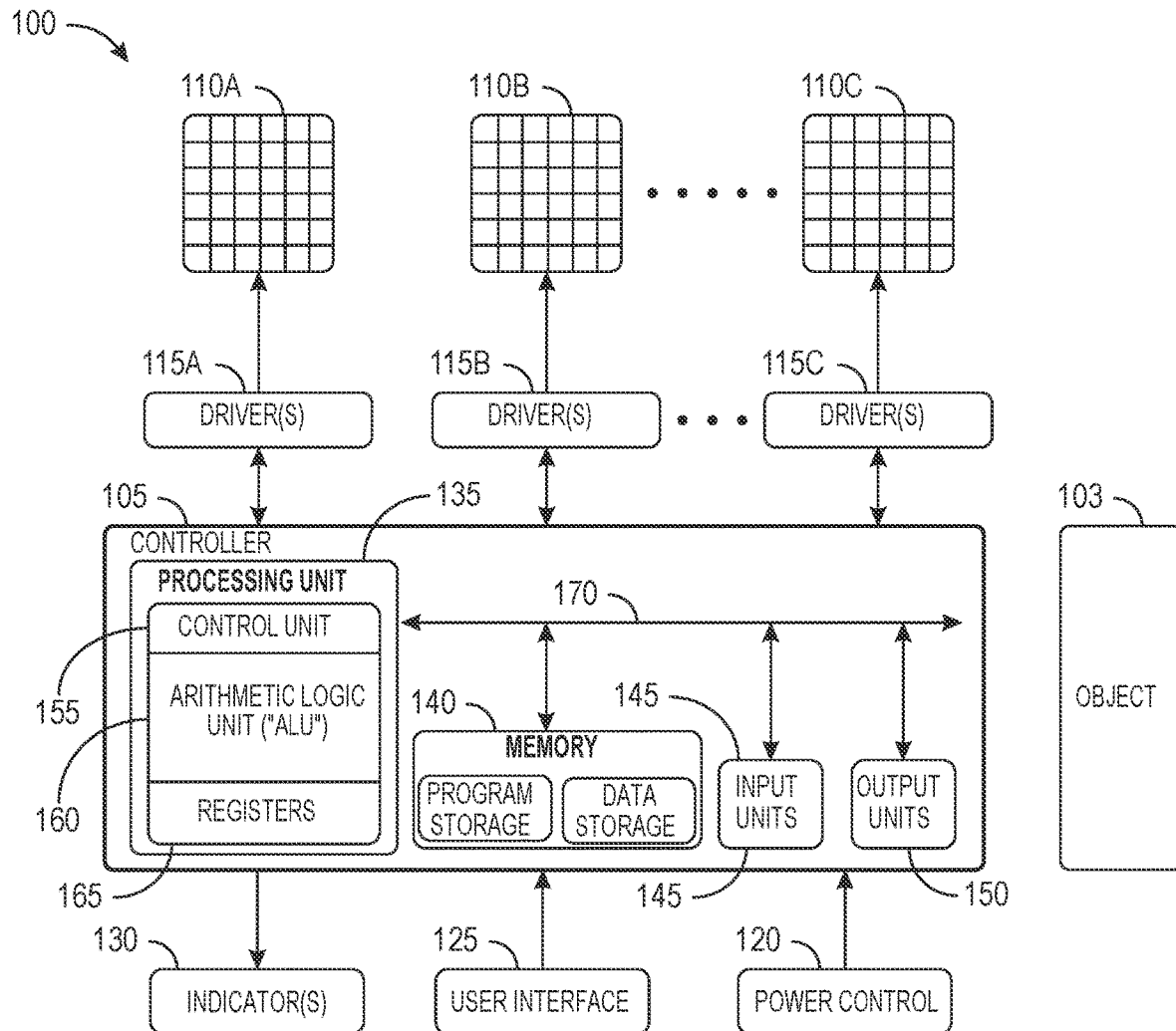
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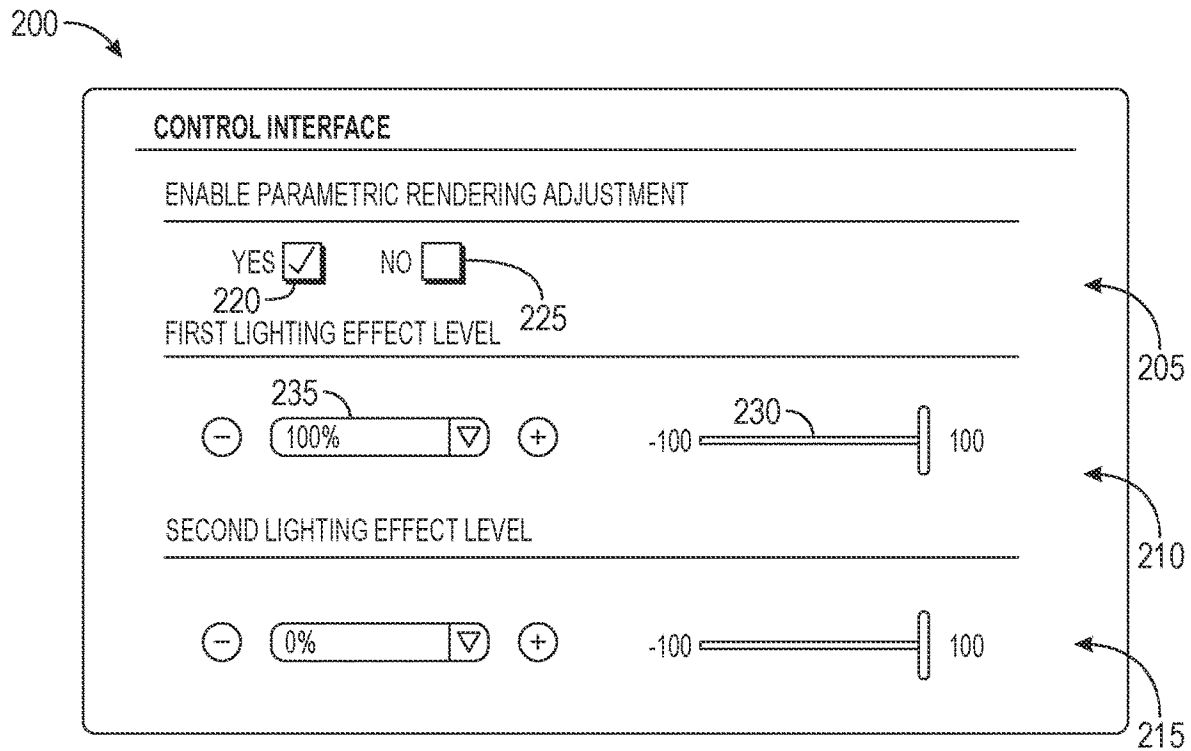


**FIG. 1**

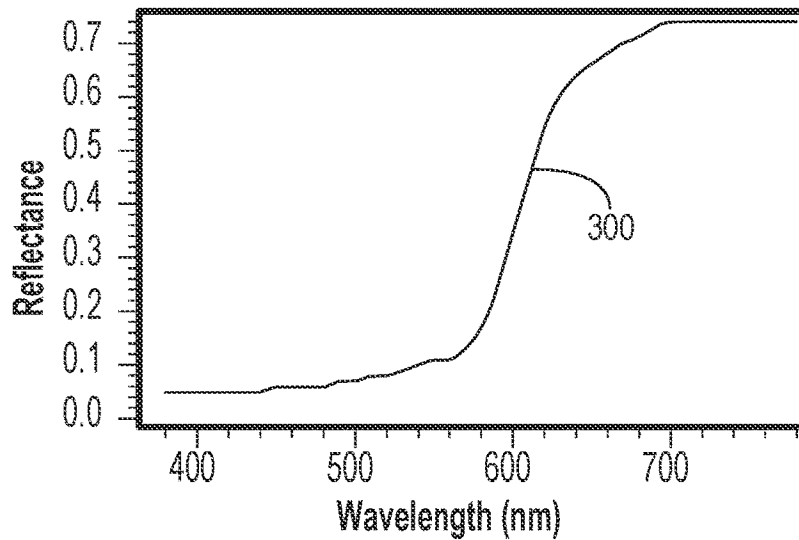


**FIG. 2**

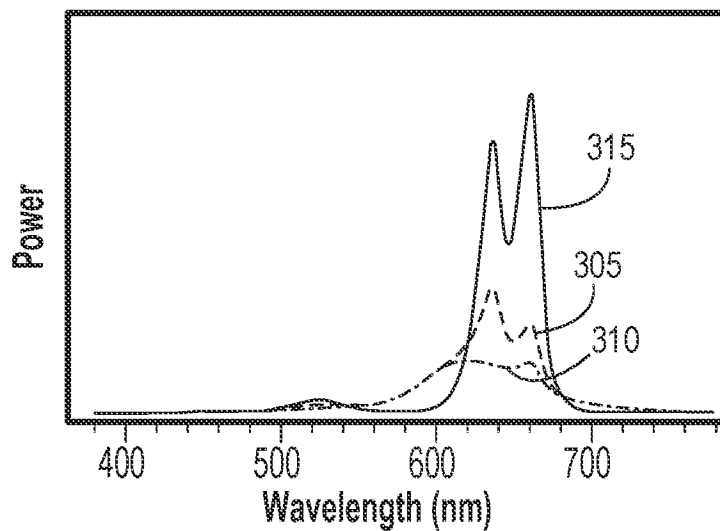




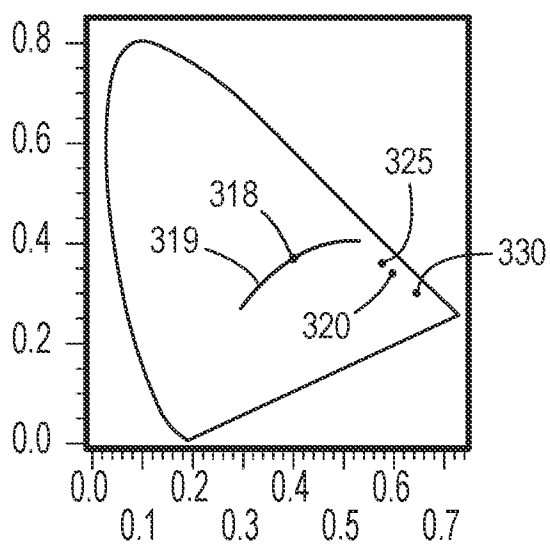
**FIG. 3**



**FIG. 4**



**FIG. 5**



**FIG. 6**

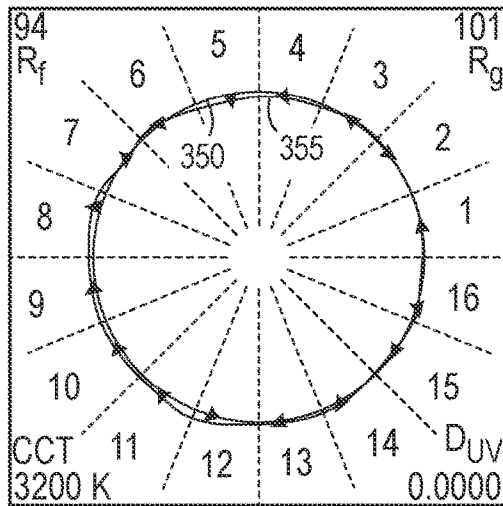


FIG. 7A

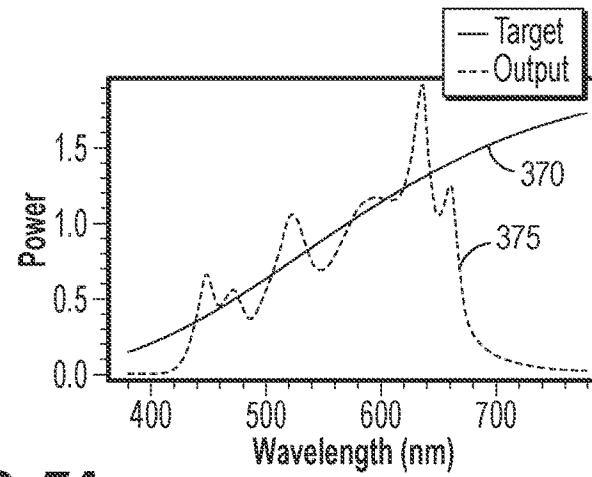


FIG. 8A

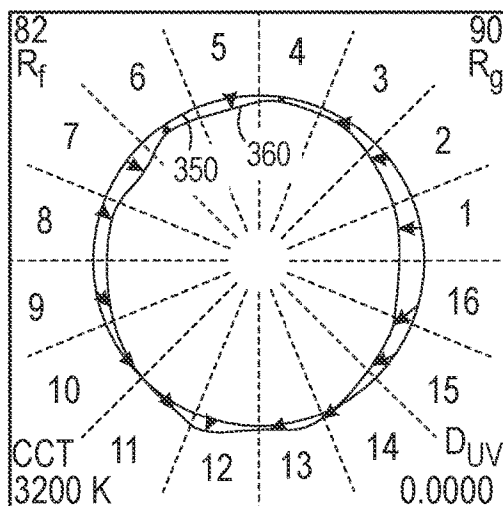


FIG. 7B

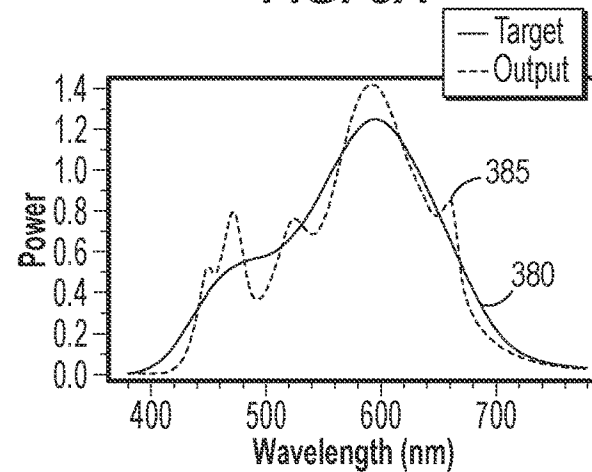


FIG. 8B

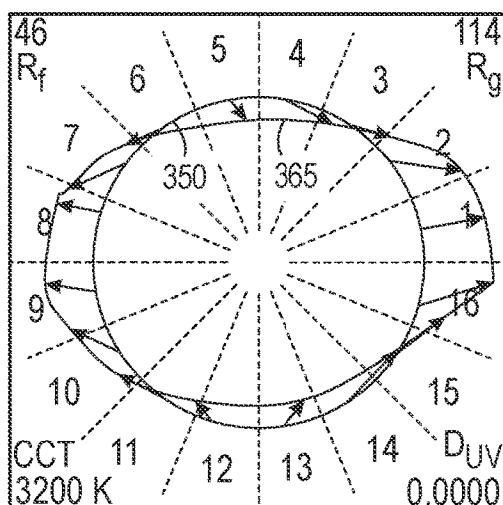


FIG. 7C

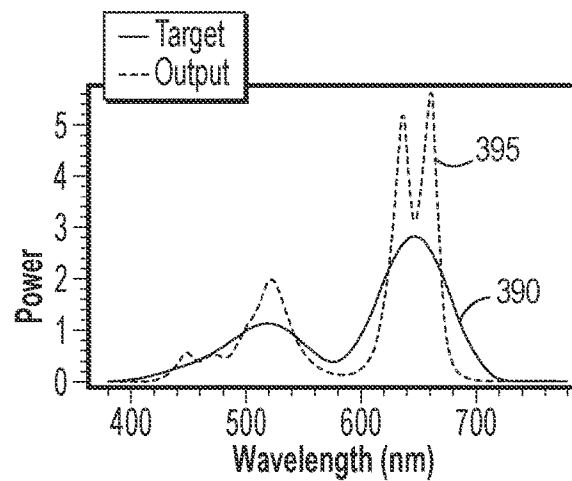


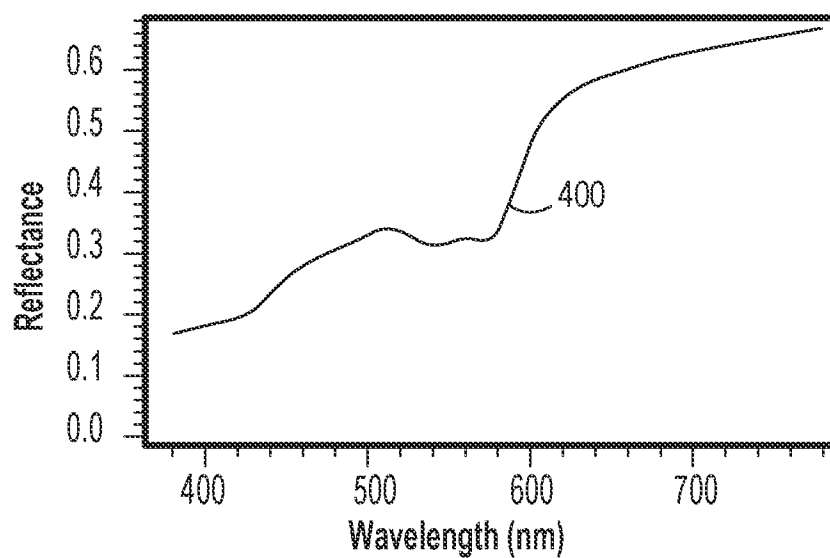
FIG. 8C

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***FIG. 9***

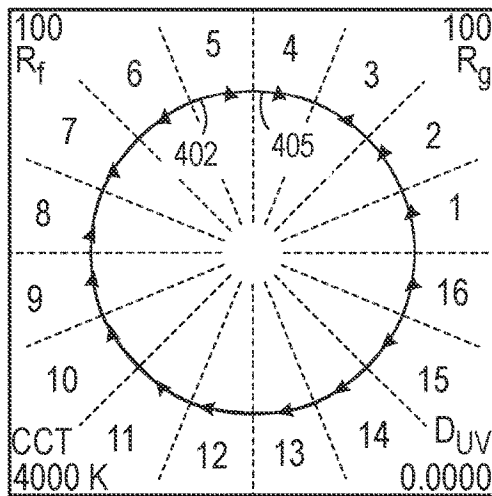


FIG. 10A

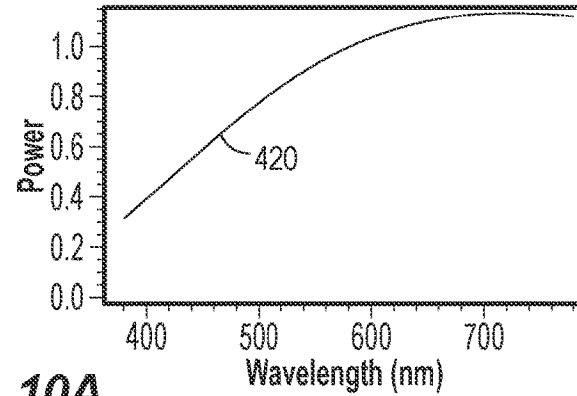


FIG. 11A

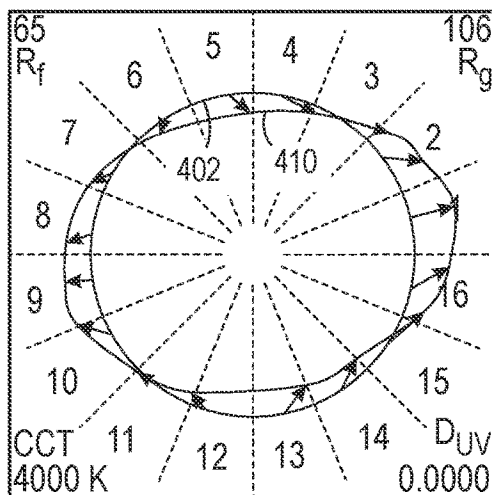


FIG. 10B

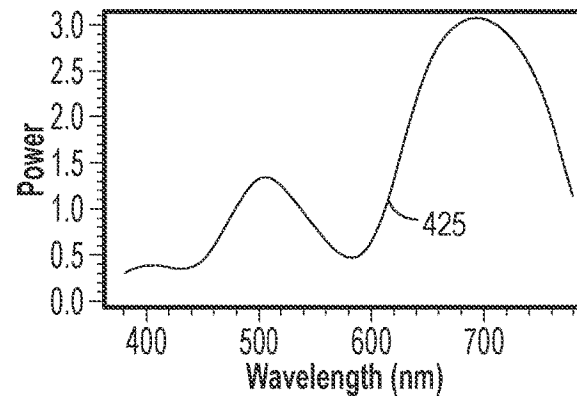


FIG. 11B

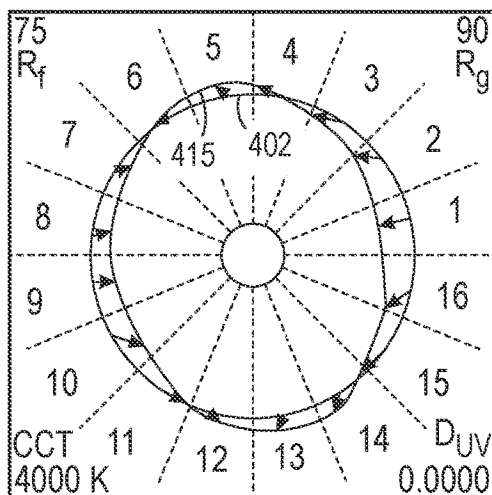


FIG. 10C

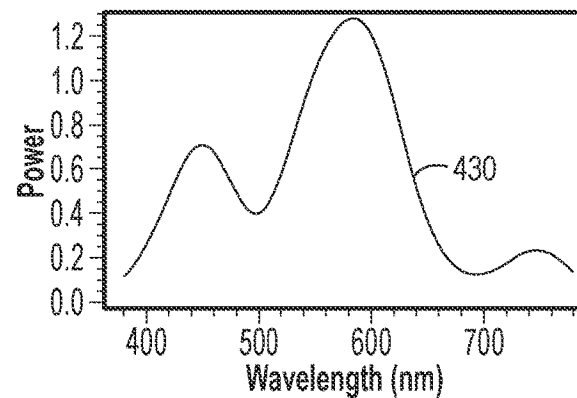


FIG. 11C

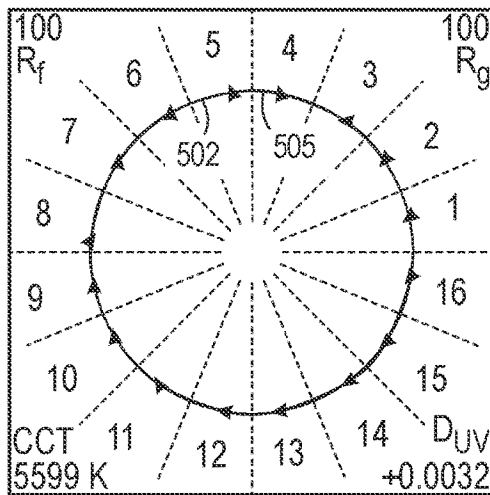


FIG. 12A

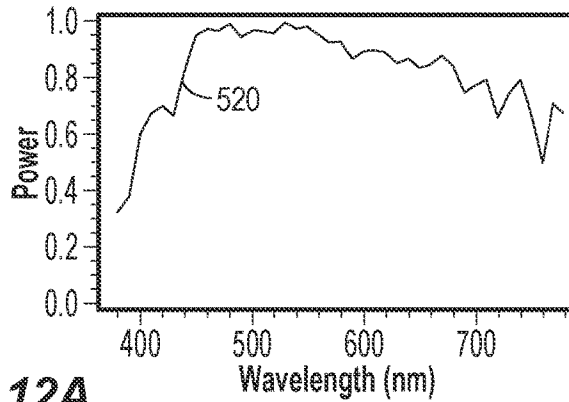


FIG. 13A

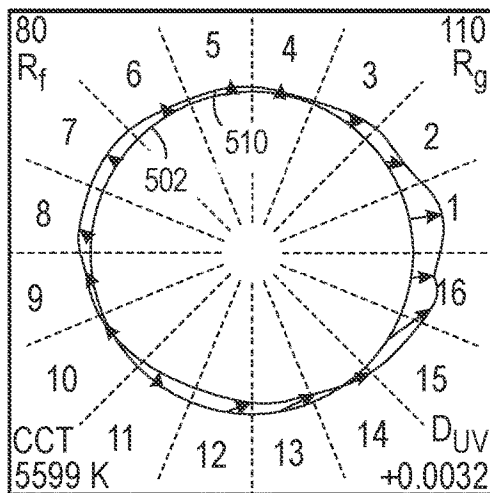


FIG. 12B

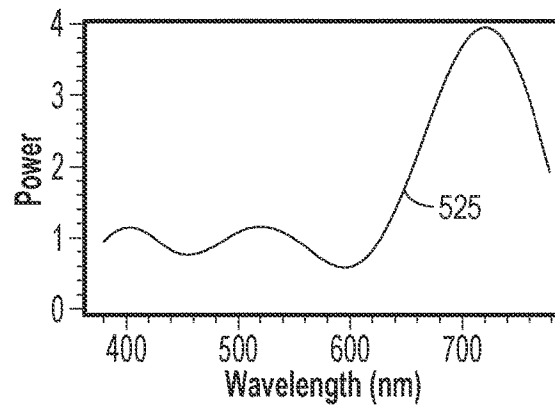


FIG. 13B

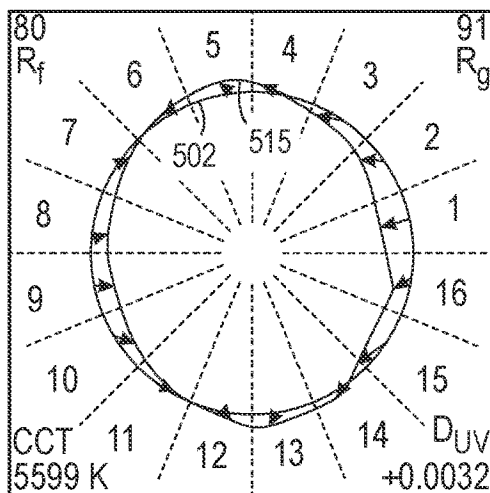


FIG. 12C

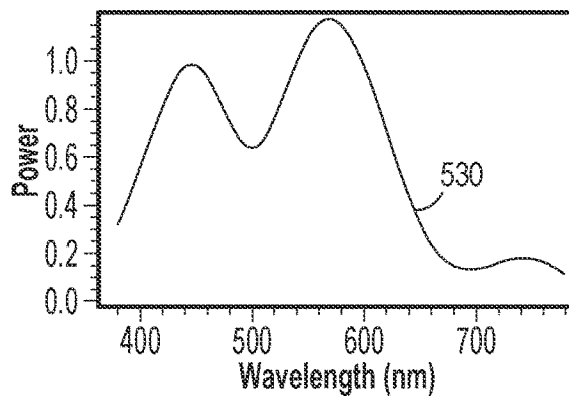


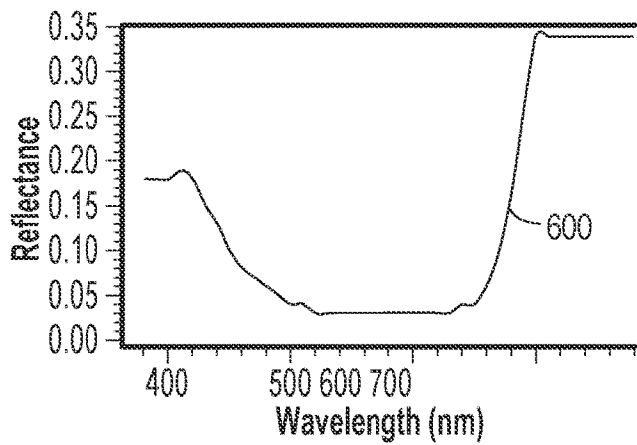
FIG. 13C

**U.S. Patent**

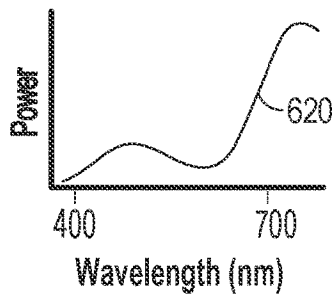
**Dec. 19, 2023**

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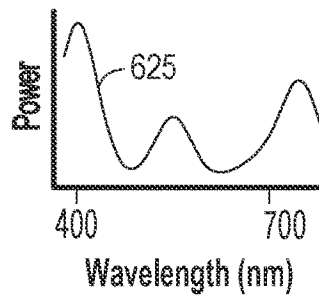
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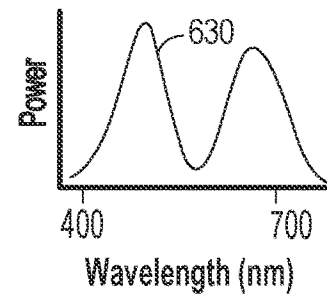
**FIG. 14**



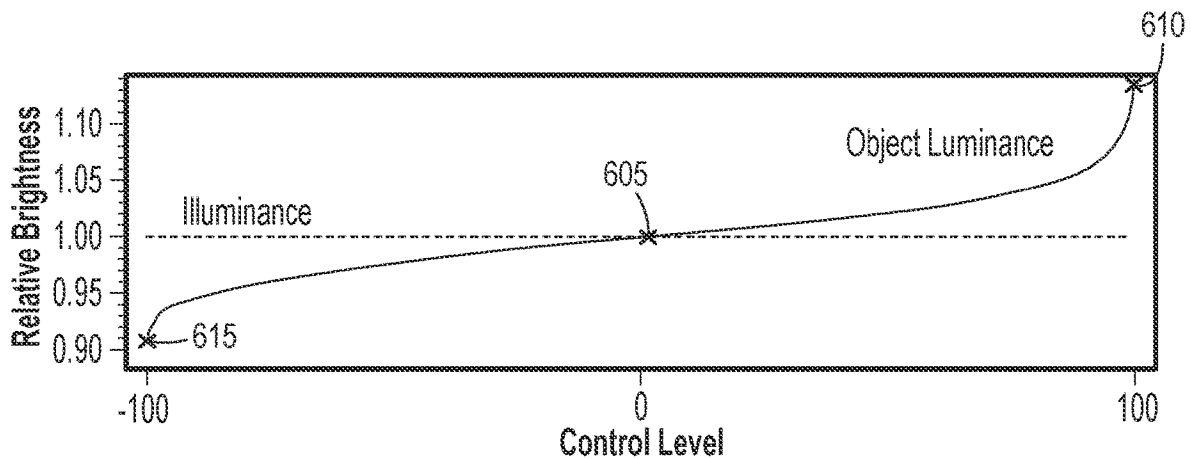
**FIG. 15A**



**FIG. 15B**

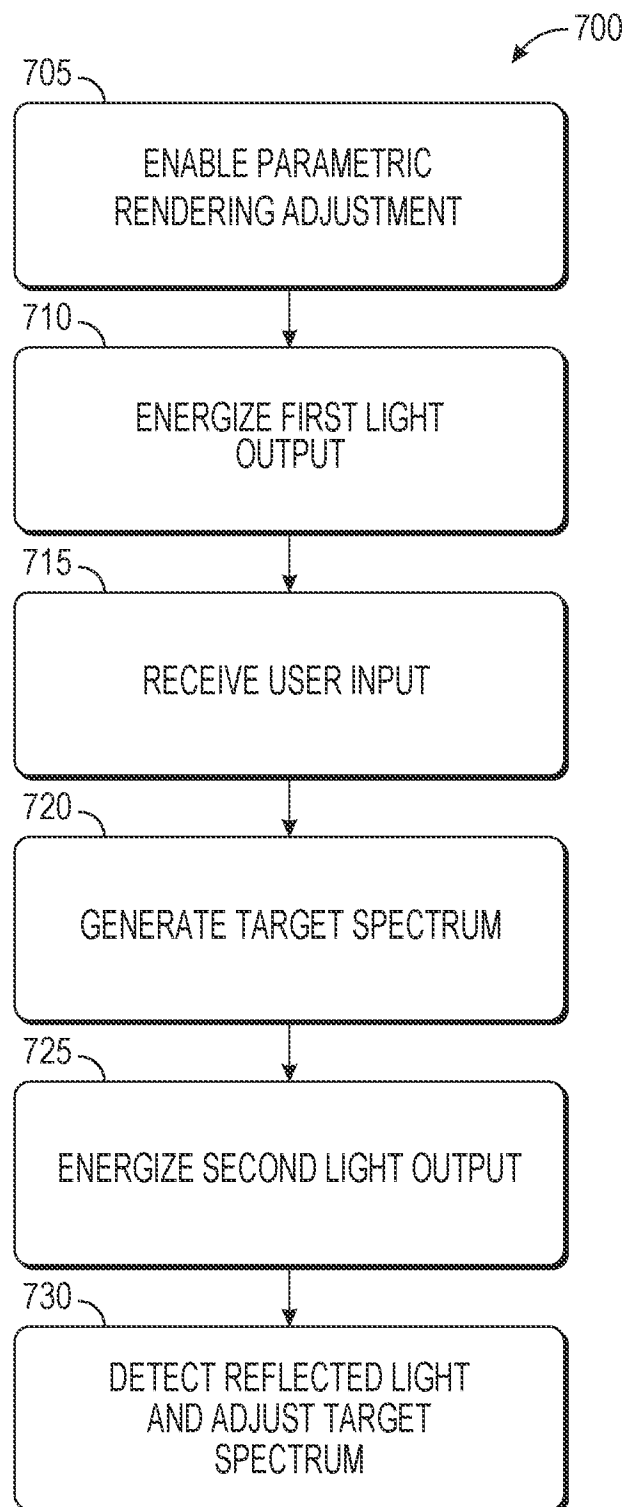


**FIG. 15C**



**FIG. 16**





**FIG. 17**

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# SYSTEMS, METHODS, AND DEVICES FOR INFLUENCING SPECTRAL CONTENT OF A LIGHT OUTPUT

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/173,286, filed Feb. 11, 2021, which claims the benefit of U.S. Provisional Patent Application No. 62/975,459, filed Feb. 12, 2020, the entire content of each of which is hereby incorporated by reference.

## FIELD

Embodiments described herein relate to influencing the spectral content of a light output.

## BACKGROUND

Lighting systems used in architecture, theaters, concert stages, and other applications may be configured to control the light produced by a light source, such as a light fixture, luminaire, array of light emitting diodes, or other lighting device.

## SUMMARY

The lighting system may be controlled in various ways to produce a desired chromaticity (i.e., color) for the output light. Holding the chromaticity of the light output while adjusting the spectral content of the light output is called metameric control. For example, U.S. Pat. No. 8,723,450, incorporated herein by reference, discloses controlling the spectral content of the output of a light fixture by modifying the output intensity value of one or more of the light sources that make up the light fixture. For example, the user may adjust upwards the power output of a red light emitting diode (“LED”) within the light fixture. After modifying the output intensity values of individual emitters, a color control and matching technique is used to identify a new set of output intensity values for the remaining emitters that maintains the desired color output. The method of adjusting spectral content of a light output disclosed in U.S. Pat. No. 8,723,450 is specific to a given light fixture because the control adjusts the output of the specific light sources (e.g., individual LED) contained within the light fixture. However, different light fixtures have different light sources, so the method disclosed in U.S. Pat. No. 8,723,450 is not readily applicable or generic across different light fixtures. Finally, although the user is able to adjust the spectral content of the light output in the method disclosed in U.S. Pat. No. 8,723,450, the user is not provided control over or insight into how, for example, an object will appear when illuminated by the light output with the modified spectral content. In other words, the user is able to adjust the spectral content of the light output in U.S. Pat. No. 8,723,450 but does not have control over the lighting effect or effects (i.e., as perceived by a human observer or camera observer) created by the changing spectral content.

Embodiments described herein address this and other technical problems by analyzing aspects of perceived light to adjust the perceived appearance of the light output according to user specifications. The aspects of the perceived light controlled by embodiments described herein may include, for example, how the user perceives an object within the light output. In this way, the user alters the look

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and/or feel of the object according to how the user wants the object to appear. As a result, the user can alter how the object appears without altering the chromaticity of the light output. For example, the user may desire the object (e.g., human skin) to appear sickly under a metameric (constant-chromaticity) illuminant, or to appear brighter under a constant-power illuminant, or both.

Methods described herein provide for control of a light fixture, the method including energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receiving a user input representative of a desired adjustment of a lighting effect, generating a target spectrum based on the user input, and energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution. The second power distribution approximates the target spectrum.

Lighting control systems described herein include one or more light fixtures, one or more driver circuits, a user interface, and a controller. The one or more driver circuits are configured to provide drive signals to the one or more light fixtures. The user interface is configured to receive an input related to a light output of the one or more light fixtures. The input is representative of an adjustment of a lighting effect. The controller is connected to the one or more driving circuits and the user interface. The controller includes a processor and a memory. The controller is configured to energize the one or more light fixtures to produce a first light output with a first chromaticity and a first spectral power distribution, receive the input representative of the adjustment of the lighting effect, generate a target spectrum based on the input, and energize the one or more light fixtures to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

Controllers for controlling a light output of a light fixture described herein include a non-transitory computer readable medium and a processor. The controller includes computer executable instructions stored in the computer readable medium for controlling operation of the controller to energize the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution, receive an input representative of an adjustment of a lighting effect, generate a target spectrum based on the user input, and energize the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximates the target spectrum.

It should be understood that the terms spectral match, spectrally matching, and the like (including similar terms with fixed or constant) refer to the application of an optimization procedure for spectrally matching the output composite light spectrum of the composite light source to a given target spectrum. It should be understood that the spectral match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints. Similarly, the terms chromaticity match, chromaticity matching, constant chromaticity, fixed chromaticity, and the like refer to the application of an optimization procedure for matching CIE chromaticity coordinates of the output composite light source spectrum to CIE chromaticity coordinates of a given target spectrum. It should be understood that the chromaticity match provided by the composite light source will not necessarily be identical to the target spectrum. But, it will be optimally close or as close as possible according to given system constraints.

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Before any embodiments are explained in detail, it is to be understood that the embodiments are not limited in their application to the details of the configuration and arrangement of components set forth in the following description or illustrated in the accompanying drawings. The embodiments are capable of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

In addition, it should be understood that embodiments may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic-based aspects may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processing units, such as a microprocessor and/or application specific integrated circuits (“ASICs”). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components, may be utilized to implement the embodiments. For example, “servers” and “computing devices” described in the specification can include one or more processing units, one or more computer-readable medium modules, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

Other aspects of the embodiments will become apparent by consideration of the detailed description and accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a lighting control system.

FIG. 2 is a block diagram of a lighting control system according to another embodiment.

FIG. 3 illustrates a control interface for a lighting system.

FIG. 4 is a graph of the spectral reflectance function for an object.

FIG. 5 is a graph illustrating the spectral power distribution of light reflected off the object of FIG. 4 under a default condition, a positive hue shift condition, and a negative hue shift condition.

FIG. 6 is a CIE 1931 chromaticity diagram illustrating the chromaticity of the object of FIG. 4 under the default condition, the positive hue shift condition, and the negative hue shift condition of FIG. 5.

FIG. 7A is a TM-30 color vector graphic for the default condition of FIG. 5.

FIG. 7B is a TM-30 color vector graphic for the positive hue shift condition of FIG. 5.

FIG. 7C is a TM-30 color vector graphic for the negative hue shift condition of FIG. 5.

FIG. 8A is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the default condition of FIG. 5.

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FIG. 8B is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the positive hue shift condition of FIG. 5.

FIG. 8C is a graph illustrating a target output spectral power distribution and an achieved output spectral power distribution for the negative hue shift condition of FIG. 5.

FIG. 9 is a graph of the spectral reflectance function of an object.

FIG. 10A is a TM-30 color vector graphic for a default condition for the object of FIG. 9.

FIG. 10B is a TM-30 color vector graphic for a positive chroma shift condition for the object of FIG. 9.

FIG. 10C is a TM-30 color vector graphic for a negative chroma shift condition for the object of FIG. 9.

FIG. 11A is a graph illustrating a target output spectral power distribution for the default condition of FIG. 10A.

FIG. 11B is a graph illustrating a target output spectral power distribution for the positive chroma shift condition of FIG. 10B.

FIG. 11C is a graph illustrating a target output spectral power distribution for the negative chroma shift condition of FIG. 10C.

FIG. 12A is a TM-30 color vector graphic for a default condition for a 5600K illuminant.

FIG. 12B is a TM-30 color vector graphic for an over-saturated condition for the 5600K illuminant.

FIG. 12C is a TM-30 color vector graphic for an under-saturated condition for the 5600K illuminant.

FIG. 13A is a graph illustrating a target output spectral power distribution for the default condition of FIG. 12A.

FIG. 13B is a graph illustrating a target output spectral power distribution for the oversaturation condition of FIG. 12B.

FIG. 13C is a graph illustrating a target output spectral power distribution for the undersaturation condition of FIG. 12C.

FIG. 14 is a graph of the spectral reflectance function of an object.

FIG. 15A is a target output spectral power distribution for a non-white chromaticity at a default illuminance of the object of FIG. 14.

FIG. 15B is a target output spectral power distribution for the non-white chromaticity at an increased illuminance of the object of FIG. 14.

FIG. 15C is a target output spectral power distribution for the non-white chromaticity at a decreased illuminance of the object of FIG. 14.

FIG. 16 is a graph illustrating the relative brightness of the object of FIG. 14.

FIG. 17 is a method for controlling a light output for a lighting system.

#### DETAILED DESCRIPTION

FIGS. 1 and 2 illustrate a control system 100 that can be used in, for example, a theatre, a hall, an auditorium, a hotel, a cruise ship, or the like. In some embodiments, the control system 100 is disposed within a light fixture. In other embodiments, only a portion of the control system 100 is disposed in the light fixture. The control system 100 is configured to generate a light output and project that light output onto an object 103 according to specifications of a user for how the object 103 is to appear in the light output. The object 103 may be a human (e.g., skin), an inanimate object (e.g., fruit or fabric), a wall, or the like. Additionally, the light output may be projected onto a plurality of objects 103 (e.g., a class of objects). For descriptive purposes, light

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is generally described as being projected onto the object **103**. However, in any instance where the object **103** is referenced, light can additionally be projected onto a plurality of objects **103** of the same or different classes of objects. The user specifications may alter the look and/or feel of the object **103** according to how the user wants the object to appear, which allows the user to alter how the object appears without altering the chromaticity of the light output.

The control system **100** includes a controller **105**, a plurality of light modules or light arrays **110A-110C** (e.g., light fixtures, color channels, etc.), a plurality of driver circuits **115A-115C**, a power control circuit **120**, an input mechanism **125**, and one or more indicators **130**. The controller **105** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller **105** and/or the system **100**. For example, the controller **105** includes, among other things, a processing unit **135** (e.g., a microprocessor, a microcontroller, an electronic controller, an electronic processor, or another suitable programmable device), a memory **140**, input units **145**, and output units **150**. The processing unit **135** includes, among other things, a control unit **155**, an arithmetic logic unit (“ALU”) **160**, and a plurality of registers **165** (shown as a group of registers in FIG. 1), and is implemented using a known computer architecture (e.g., a modified Harvard architecture, a von Neumann architecture, etc.). The processing unit **135**, the memory **140**, the input units **145**, and the output units **150**, as well as the various modules connected to the controller **105** are connected by one or more control and/or data buses (e.g., common bus **170**). The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the embodiments described herein. The control and/or data buses are shown generally for illustrative purposes.

In some embodiments, the control system **100** also includes a camera **175** configured to detect the light from the modules **110A-110C** reflected off of the object **103** (as shown in FIG. 1). In some embodiments, the camera **175** is a spectrometer, or another device specifically designed to detect a light spectrum. In other embodiments, the control system **100** does not include the camera **175** (as shown in FIG. 2). In these embodiments, the control system **100** operates in an open loop manner (i.e., without a closed-loop camera feedback system).

The memory **140** is a non-transitory computer readable medium and includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as a ROM, a RAM (e.g., DRAM, SDRAM, etc.), EEPROM, flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **135** is connected to the memory **140** and executes software instructions that are capable of being stored in a RAM of the memory **140** (e.g., during execution), a ROM of the memory **140** (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the control system **100** can be stored in the memory **140** of the controller **105**. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller **105** is configured to retrieve from the memory **140** and execute, among other things, instructions

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related to the control processes and methods described herein. In other embodiments, the controller **105** includes additional, fewer, or different components.

The user interface **125** is included to control the control system **100**. The user interface **125** is operably coupled to the controller **105** to control, for example, the output of the light modules **110A-110C**, and generate and provide control signals for the driver circuits **115A-115C**. The user interface **125** can include any combination of digital and analog input devices to achieve a desired level of control for the control system **100**. For example, the user interface **125** can include a computer having a display and input devices, a touch-screen display, a plurality of knobs, dials, switches, buttons, faders, or the like. In some embodiments, the user interface **125** is separated from the control system **100** (e.g., as a portable device communicatively connected to the controller **105**).

The driver circuits **115A-115C** include a first driver circuit **115A**, a second driver circuit **115B**, and a third driver circuit **115C** that are operable to provide control signals to the light modules **110A-110C**. For example, the first driver circuit **115A** is connected to a first light module **110A** for providing one or more drive signals to an array of (i.e., one or more) light sources of the first light module **110A**. The second driver circuit **115B** is connected to a second light module **110B** for providing one or more drive signals to an array of (i.e., one or more) light sources on the second light module **110B**. The third driver circuit **115C** is connected to a third light module **110C** for providing one or more drive signals to an array of (i.e., one or more) light sources on the third light module **110C**. In some embodiments, each of the light modules **110A-110C** corresponds to a color channel of a light. In other embodiments, each of the light modules **110A-110C** corresponds to a separate light fixture.

The power control circuit **120** supplies a nominal AC or DC voltage to the control system **100**. In some embodiments, the power control circuit **120** is powered by one or more batteries or battery packs. In other embodiments, the power control circuit **120** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz. The power control circuit **120** is also configured to supply lower voltages to operate circuits and components within the control system **100**.

As illustrated in FIGS. 1 and 2, the controller **105** is connected to light modules **110A-110C**. In some embodiments, each light module **110A-110C** is a chip-on-board (“COB”) light source. A three light module embodiment is illustrated for exemplary purposes only. In other embodiments, four or more light modules are used to further enhance the system **100**’s ability to produce visible light. Conversely, in other implementations, fewer than three light modules are used (i.e., one or two light modules). In some embodiments, the light modules **110A-110C** are light emitting diode (“LED”) light modules. In some embodiments, the light modules **110A-110C** produce white light. In other embodiments, the light modules **110A-110C** produce colored light (i.e., non-white light).

The control system **100** further includes a control interface **200** (see FIG. 3) for controlling a visual appearance of the light output light from the light modules **110A-110C** that is, for example, reflected from the object **103**. In some embodiments, the control interface **200** is included in the user interface **125**. The control interface **200** is, for example, a graphical user interface (“GUI”) that is displayed on a monitor or similar display. In some embodiments, the con-

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trol interface **200** is a physical interface and includes one or more buttons, knobs, dials, faders, or the like.

The illustrated control interface **200** includes an optional enable parametric rendering adjustment section **205**, a first lighting effect level section **210**, and a second lighting effect level section **215**. The enable parametric rendering adjustment section **205** includes a YES checkbox **220** and a NO checkbox **225**. The checkboxes **220** and **225** are used to select or deselect parametric rendering adjustment (i.e., control based on visual appearance of the lighting effect).

The parametric rendering adjustment can use the first lighting effect level section **210** and/or the second lighting effect level section **215** to implement lighting effects that modify the appearance of light, for example, reflected off the object **103**. The first and second lighting effect level of the sections **210**, **215** may include control of quality, luminance, hue, power, color temperature, or the like. The first and second lighting effects are generic to any light fixture and allows the user to control effects to the best of the system's ability, regardless of what light fixture is used.

In some embodiments, the parametric rendering adjustment includes more than two lighting effect level sections. In the illustrated embodiment, each of the lighting effect level sections includes a maximum value and a minimum value. For the purposes of this embodiment, the maximum value is a value of positive 100 (e.g., oversaturation). The minimum value is a value of negative 100 (e.g., undersaturation). For example, the maximum undersaturation value is the inverse of the maximum oversaturation value. The first and second lighting effect level sections **210**, **215** each include a slider **230** and a drop-down menu **235**. The slider **230** ranges from negative 100 to positive 100 (e.g., from undersaturation to oversaturation). The drop-down menu **235** ranges from -100% to 100%. In other embodiments, the first and second lighting effect level sections **210** include different selection mechanisms. In conventional lighting control systems, the first and second lighting effects are not directly controllable along a continuum (i.e., negative 100 to positive 100). In this way, the control interface **200** permits the user to precisely control aspects of the output light that would not otherwise be directly adjustable and controllable by conventional controls, all while maintaining the same output chromaticity. Non-limiting examples of lighting effects to be controlled by the interface **200** are described in further detail herein.

With reference to FIGS. 4-8C, in one embodiment, the lighting effect controlled by the interface **200** is the hue shift of an object illuminated by the light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different colors and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. 4, a spectral reflectance function **300** of a first example object (e.g., a grapefruit) is illustrated. The spectral reflectance function **300** illustrates how incoming light will be reflected off the object—with longer wavelengths (e.g., greater than 600 nm) reflected more than shorter wavelengths. With the control interface **200**, the hue of the first example object may be controlled between a default condition, a positive hue shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative hue shift condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the color appearance of the first example object without changing the chromaticity of the output light. For each of these conditions, the resulting spectral power distribution of light

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reflected off the first example object (i.e., the grapefruit's rendered spectra) is illustrated in FIG. 5. Specifically, the rendered spectrum **305** is for the default condition, the rendered spectrum **310** is for the positive hue shift condition, and the rendered spectrum **315** for the negative hue shift condition.

With reference to FIG. 6, each of these rendered spectra **305**, **310**, **315** correspond to an object chromaticity **320**, **325**, **330** as illustrated in a CIE 1931 chromaticity diagram. More specifically, the first example object appears to an observer at a default chromaticity **320** with an output light chromaticity **318**. In the illustrated embodiment, the output light chromaticity **318** is on the Planckian locus **319** and is held constant. The first example object appears to an observer at a positive hue shift chromaticity **325** in the positive hue shift condition and at a negative hue shift chromaticity **330** in the negative hue shift condition. As such, the control interface **200** permits a user to adjust the chromaticity of the light reflected off of the first example object while maintaining the output light chromaticity constant.

With reference to FIGS. 7A-7C, color vector graphics are illustrated according to the TM-30 standard. In general, a color vector graphic shows how the color evaluation samples, representative of a wide range of objects, are likely to undergo either a saturation (chroma) shift, a hue shift, or both. The color vector graphic is divided into 16 equal sections with for, example, section **1** representative of red and section **9** representative of cyan. The reference illuminant is normalized to a reference circle **350** and the gamut of the light source is plotted relative to the circle as a distorted circle (e.g., **360** of FIG. 7B). Arrows that point radially into the reference circle **350** indicate areas of decreased saturation while areas that point radially out of the reference circle **350** indicate areas of increased saturation. Arrows that do not point directly to the center of the circle **350** or directly away from the center **350** of the circle are representing hue shift. In short, the color vector graphics can be used to illustrate how objects will appear in an output light relative to a reference light source (e.g., daylight).

With continued reference to FIGS. 7A-7C, the color vector graphics are illustrated for the default condition (FIG. 7A), the positive hue shift condition (FIG. 7B), and the negative hue shift condition (FIG. 7C). In FIG. 7A, the light source output gamut **355** closely tracks the reference circle **350** in the default condition. Attributes of the output light ( $R_p$ ,  $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. 7A. In FIG. 7B, the light source output gamut **360** is adjusted in the positive hue shift condition, and in FIG. 7C, the light source output gamut **365** is adjusted in the negative hue shift condition. The CCT value of 3200 K and  $D_{uv}$  of 0.0000 is held constant for FIGS. 7A-7C.

To achieve the default, positive hue shift, and negative hue shift conditions desired by the user, the controller **105** determines the corresponding target output light spectrums **370**, **380**, **390** illustrated in FIGS. 8A-8C. The target output light spectrums **370**, **380**, **390** correspond to the default, positive hue shift, and negative hue shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., **318**). In other words, there are numerous metamers for the target chromaticity (e.g., **318**) and the controller **105** selects the metamer that results in the hue shift condition desired by the user. The selection of the metamer for a desired hue shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not



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limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

With the target output light spectrums **370**, **380**, **390** determined, conventional spectral matching techniques (such as those disclosed in U.S. Pat. No. 6,683,423; incorporated herein) are utilized to determine how to drive the actual light emitters contained within a given fixture. In other words, the control system **100** determines an idealized target output spectrum for controlling the hue shift of the first example object. As one example, the actual output spectral power distribution achieved for an example light fixture containing eight primary emitters is illustrated as output spectrum distributions **375**, **385**, **395** on FIGS. **8A-8C**. In other words, the output spectrum distributions **375**, **385**, **395** illustrate a given light fixture's best ability to match the target output light spectrums **370**, **380**, **390**.

In summary, FIGS. **4-8C** illustrate the implementation of control for hue shift of a first example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the light that is reflected off of the first example object (i.e., change in reflected light chromaticities **320**, **325**, **330**), while holding the output light chromaticity constant (e.g., chromaticity **318**). The hue shift of the first example object is not directly adjustable with conventional controls.

With reference to FIGS. **9-11C**, in another embodiment, the lighting effect controlled by the interface **200** is the chroma shift of an object illuminated by the light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be different saturations and can be adjusted by a user while holding the output light chromaticity constant.

With reference to FIG. **9**, a spectral reflectance function **400** of a second example object (e.g., one example of human skin) is illustrated. The spectral reflectance function **400** illustrates how incoming light will be reflected off the second example object. With the control interface **200**, the chroma (i.e., saturation) of the second example object may be controlled between a default condition, a positive chroma shift condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a negative chroma shift condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the saturation appearance of the second example object without changing the chromaticity of the output light. As such, the  $R_g$  value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **10A-10C**, the color vector graphics are illustrated for the default condition (FIG. **10A**), the positive chroma shift condition (FIG. **10B**), and the negative chroma shift condition (FIG. **10C**). In FIG. **10A**, the light source output gamut **405** closely tracks the reference circle **402** in the default condition and the  $R_g$  value is 100. Attributes of the output light ( $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. **10A**. In FIG. **10B**, the light source output gamut **410** is adjusted in the positive chroma shift condition with a  $R_g$  value of 106, and in FIG. **10C**, the light source output gamut **415** is adjusted in the negative chroma shift condition with a  $R_g$  value of 90. The CCT value of 4000 K and  $D_{uv}$  of 0.0000 is held constant for FIGS. **10A-10C**.

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With reference to FIGS. **11A-11C**, for each of the desired chroma-shifts in the second example object there is a corresponding output target spectrum power distribution **420**, **425**, **430**. The target output light spectrums **420**, **425**, **430** correspond to the default, positive chroma shift, and negative chroma shift conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=4000 K and  $D_{uv}$ =0.0000). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the chroma shift condition for the second example object desired by the user. The selection of the metamer for a desired chroma shift may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **420**, **425**, **430** are generalized targets (similar to the target spectrum **370**, **380**, **390**) that are applicable to any type of light fixture being used. Conventional target spectral matching techniques may be utilized to drive emitters in a given light fixture in order to approximate the target.

In summary, FIGS. **9-11C** illustrate the implementation of control for chroma shift of a second example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the saturation of the light reflected off of the second example object, while holding the output light chromaticity constant. The chroma shift of the second example object is not directly adjustable with conventional controls.

With reference to FIGS. **12A-13C**, in another embodiment, the lighting effect controlled by the interface **200** is the generalized saturation appearance of object(s) (i.e.,  $R_g$  value) of an approximately 5600 K light output of the light arrays **110A-110C**. With the control interface **200**, the generalized saturation may be controlled between a default condition, a generalized oversaturation condition (e.g., +100 adjustment of the first lighting effect level section **210**), and a generalized undersaturation condition (e.g., -100 adjustment of the first lighting effect level section **210**). In other words, the control interface **200** is utilized by a user to control the generalized saturation appearance of object(s) without changing the chromaticity of the output light. As such, the  $R_g$  value of the output light is adjusted to be greater than or less than 100.

With reference to FIGS. **12A-12C**, the color vector graphics are illustrated for the default condition (FIG. **12A**), the generalized oversaturation condition (FIG. **12B**), and the generalized undersaturation condition (FIG. **12C**). In FIG. **12A**, the light source output gamut **505** closely tracks the reference circle **502** in the default condition and the  $R_g$  value is 100. Attributes of the output light ( $R_g$ , CCT,  $D_{uv}$ ) in the default condition are also listed in FIG. **12A**. In FIG. **12B**, the light source output gamut **510** is adjusted in the generalized oversaturation condition with a  $R_g$  value of 110, and in FIG. **12C**, the light source output gamut **515** is adjusted in the generalized undersaturation condition with a  $R_g$  value of 91. The CCT value of 5599 K and  $D_{uv}$  of 0.0032 is held constant for FIGS. **12A-12C**.

With reference to FIGS. **13A-13C**, for each of the desired generalized saturation levels there is a corresponding output

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target spectrum power distribution **520, 525, 530**. The target output light spectrums **520, 525, 530** correspond to the default, oversaturated, and undersaturated conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., CCT=5599 K and  $D_{uv}=0.0032$ ). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the generalized saturation level desired by the user. The selection of the metamer for a desired saturation level may be preprogrammed into the memory **140** as a look-up table, for example. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The target output light spectrums **520, 525, 530** are generalized targets (similar to the target spectrum **370, 380, 390**) that are applicable to any type of light fixture being used.

In summary, FIGS. **12A-13C** illustrate the implementation of control for generalized saturation appearance of object(s) in an approximately 5600K illuminant (i.e., an example light effect level), while holding the output light chromaticity constant. The generalized saturation of a 5600K illuminant is not directly adjustable with conventional controls.

With reference to FIGS. **14-16**, in another embodiment, the lighting effect controlled by the interface **200** is the relative luminance of an object illuminated by a non-white light output of the light arrays **110A-110C**. With this control, the illuminated object **103** may appear to an observer (i.e., a human or camera) to be brighter or darker and can be adjusted by a user while holding the output light chromaticity constant at a non-white color and equal luminous flux.

With reference to FIG. **14**, a spectral reflectance function **600** of a third example object (e.g., a purple scarf) is illustrated. The spectral reflectance function **600** illustrates how incoming light will be reflected off the third example object. With the control interface **200**, the luminance (i.e., brightness) of the third example object may be controlled between a default condition (point **605** in FIG. **16**), an increased relative luminance condition (point **610** in FIG. **16**) (e.g., +100 adjustment of the first lighting effect level section **210**), and a decreased relative luminance condition (point **615** in FIG. **16**) (e.g., -100 adjustment of the first lighting effect level section **210**). The minimum (e.g., -100 from the interface **200** of FIG. **3**) and maximum (e.g., +100 from the interface **200** of FIG. **3**) are defined as the extremes of the lighting effect adjustment. The changes that occur to the target output spectrum between the spectrums **625, 630** for the minimum and maximum control levels, respectively, can then be mapped (e.g., linearly) to produce a target spectrum for control values between -100 and 100 for a controllable lighting effect. In other words, the control interface **200** is utilized by a user to control the luminance of the third example object without changing the chromaticity of the output light—which in this example is a blue output light. The brightness of the third example object is being adjusted relative to the rest of the scene illuminated, since the luminous flux of the output light is held constant.

With reference to FIGS. **15A-15C**, for each of the desired relative brightnesses of the third example object there is a corresponding output target spectrum power distribution

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**620, 625, 630**. The target output light spectrums **620, 625, 630** correspond to the default, increased relative brightness, and decreased relative brightness conditions, respectively, and may be determined by selecting one of the many possible metamers for the target chromaticity (e.g., blue, or "steel blue"). In other words, there are numerous metamers for the target chromaticity and the controller **105** selects the metamer that results in the relative brightness condition for the third example object desired by the user. The selection of the metamer for a desired relative luminance may be preprogrammed into the memory **140** as a look-up table, for example. The target output light spectrums **620, 625, 630** are generalized targets (similar to the target spectrums **370, 380, 390**) that are applicable to any type of light fixture being used.

Although the described embodiment uses a look-up table to calculate a metamer, in other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof.

In summary, FIGS. **14-16** illustrate the implementation of control for relative brightness of a third example object illuminated by a light fixture (i.e., an example light effect level). With the control interface **200**, a user adjusts the luminance of the light reflected off of the third example object relative to its surroundings, while holding the output light chromaticity constant at a non-white color and equal luminous flux. The relative luminance of the third example object illuminated by non-white light is not directly adjustable with conventional controls.

FIG. **17** illustrates a method **700** for using the control system **100** to adjust a lighting effect of the output light from light arrays **110A-110C**. Various steps described herein with respect to the process **700** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial manner of execution.

In some embodiments, the user enables the parametric rendering adjustment and alters the first lighting effect level **210** and/or the second lighting effect level **215** on the control interface **200** (see FIG. **3**) to control the visual appearance of light on the object **103** (STEP **705**). In other embodiments, enabling parametric rendering adjustment is not specifically required. Before any adjustments are made, the method **700** includes energizing the light fixture to produce a first light output with a first chromaticity and a first spectral power distribution (STEP **710**). In other words, the light fixture generates a default light output. The controller **105** receives signals related to a user input that is representative of a desired adjustment of a lighting effect (STEP **715**). The desired adjustment of a lighting effect may include adjustment of the Illumination Engineering Society ("IES") Technical Memorandum 30 ("TM-30")  $R_g$  value of the light output; adjustment of a hue shift in an object illuminated by the light output; or adjustment of a chroma shift in an object illuminated by the light output. In other embodiments, the desired adjustment of a lighting effect may include adjustment of one or more parameters or metrics of a light output including but not limited to; Television Lighting Consistency Index ("TLCT"); Color Rendering Index ("CRI")  $R_a$ ; CRI  $R_9$ ; Spectral Similarity Index ("SSI"); TM-30  $R_p$ ; TM-30  $R_g$ ; TM-30  $R_{cs,h1}$ ; TM-30  $R_{f,h1}$ ; TM-30 Annex E's PVF (Preference, Vividness, Fidelity) values; Color Quality

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Scale ("CQS"); Pigment/dye/colorant alignment; Skin tone quality; Vibrance/richness; Increase or decrease in fluorescence or excitation of optical brighteners; generalized Cool/Warm appearance shift; Light source selection (e.g., tungsten 3200K vs HID 3200K vs fluorescent 3200K). Such adjustments may be applied independently or simultaneously in any combination of multiple parameters. In other embodiments, the desired adjustment of a lighting effect includes adjustment of a relative luminance of an object illuminated by the light output. In a further embodiment the desired adjustment of a lighting effect is to adjust skin tone rendition by suppressing or enhancing the cyan wavelengths. This adjustment, while maintaining a chromaticity match or constant chromaticity, provides the user the ability to tune the appearance of skin tones both to the eye and to a camera.

The method 700 further includes generating a target output light spectrum based on the user input received (STEP 720). In some embodiments, the target spectrum is retrieved from a look-up table stored in the memory 140. In other embodiments, the metamer could also be calculated by methods including, but not limited to, live calculation within the luminaire, live calculation within the controller, stored spectrum, spectrum measured live using a suitable sensor, chromaticity point measured live using a suitable sensor, further input from the user, learned behavior based on a user's previous selections, learned behavior based on a user's stored preferences, or combinations thereof. The method 700 includes energizing the light fixture to produce a second light output with the first chromaticity and a second spectral power distribution (STEP 725). The second spectral power distribution approximates or matches the target spectrum and will depend on the type of light fixture utilized to create the target spectrum.

The inputted first and/or second lighting effect levels 210, 215 are used to modify a spectrum of light produced by the light modules 110A-110C. If the appearance of the object 103 is not satisfactory, the user can modify the first lighting effect level 210 and/or the second lighting effect level 215 on the control interface 200. In this way, the control is open-loop and based on user observations and adjustments. As such, the controller 105 is configured to dynamically alter the light output to achieve a desired visual appearance of the object 103, for example. In some embodiments, the light projected onto the object 103 can be white light or colored light (i.e., light other than white light), as shown in FIGS. 14-16.

In some embodiments, the camera 175 can be used to detect a reflectance of the light off of the object 103 (STEP 730). Based on the reflectance of light off of the object 103, as detected by the camera 175, further adjustments to the target output light spectrum may be made. In this sense, the control may provide a closed-loop system that detects and measures the lighting effect being adjusted. In some embodiments, STEP 730 is not included.

Thus, embodiments described herein provide, among other things, systems, methods, and devices for controlling a light output based on a visual appearance of one or more objects. Various features and advantages are set forth in the following claims.

What is claimed is:

1. A lighting control system comprising:
  - one or more light sources;
  - one or more driver circuits configured to provide drive signals to the one or more light sources;

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an interface configured to receive an input related to a light output of the one or more light sources, the input being related to an adjustment of a lighting effect; and a controller connected to the one or more driving circuits and the interface, the controller including a processor and a memory, the controller configured to:

control the one or more light sources to produce a first light output with a first chromaticity and a first spectral power distribution,

receive the input related to the adjustment of the lighting effect,

generate a target spectrum based on the input, and control the one or more light sources to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

2. The lighting control system of claim 1, wherein the first chromaticity is a non-white color.

3. The lighting control system of claim 1, wherein the interface includes a selection mechanism for selecting a value for the lighting effect.

4. The lighting control system of claim 3, wherein the value for the lighting effect can have a positive value or a negative value.

5. The lighting control system of claim 4, wherein the positive value corresponds to oversaturation and the negative value corresponds to undersaturation.

6. The lighting control system of claim 1, wherein the one or more light sources include one or more chip-on-board ("COB") light sources.

7. The lighting control system of claim 1, further comprising:

a camera configured to detect light from the one or more light sources that is reflected off of an object.

8. The lighting control system of claim 7, wherein the camera is a spectrometer.

9. The lighting control system of claim 7, wherein the target spectrum is modified based on the light that is reflected off of the object.

10. The lighting control system of claim 1, wherein the lighting effect is one selected from the group consisting of: the TM-30  $R_g$  value of the light output, a hue shift of the light reflected by an object illuminated by the light output, a chroma shift of the light reflected by an object illuminated by the light output, a Television Lighting Consistency Index ("TLCI") value of the light output, a Color Rendering Index ("CRI")  $R_a$  value of the light output, a Spectral Similarity Index ("SSI") value of the light output, the relative luminance of an object illuminated by the light output, the TM-30  $R_y$  value of the light output, the TM-30  $R_{cs,h1}$  value of the light output, and the TM-30  $R_{f,h1}$  value of the light output.

11. A method for controlling a light source, the method comprising:

controlling the light source to produce a first light output with a first chromaticity and a first spectral power distribution;

receiving an input related to a desired adjustment of a lighting effect;

generating a target spectrum based on the input; and controlling the light source to produce a second light output with the first chromaticity and a second spectral power distribution, the second power distribution approximating the target spectrum.

12. The method of claim 11, wherein the first light output has a first lumen output and the second light output has a second lumen output equal to the first lumen output.



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13. The method of claim 11, further comprising:  
receiving, via a selection mechanism of the interface, a  
value for the lighting effect.

14. The method of claim 13, wherein the value for the  
lighting effect can have a positive value or a negative value. 5

15. The method of claim 14, wherein the positive value  
corresponds to oversaturation and the negative value corre-  
sponds to undersaturation.

16. The method of claim 11, further comprising:

detect light from the one or more light sources that is 10  
reflected off of an object; and  
modifying the target spectrum based on the light that is  
reflected off of the object.

17. The method of claim 11, wherein generating the target  
spectrum based on the input includes retrieving the target 15  
spectrum from a table stored in a memory.

18. The method of claim 11, wherein the lighting effect is  
one selected from the group consisting of: the TM-30  $R_g$   
value of the light output, a hue shift of the light reflected by  
an object illuminated by the light output, a chroma shift of 20  
the light reflected by an object illuminated by the light  
output, a Television Lighting Consistency Index ("TLCT")  
value of the light output, a Color Rendering Index ("CRI")  
Ra value of the light output, a Spectral Similarity Index  
("SST") value of the light output, the relative luminance of 25  
an object illuminated by the light output, the TM-30  $R_f$  value

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of the light output, the TM-30  $R_{cs,h1}$  value of the light  
output, and the TM-30  $R_{fh1}$  value of the light output.

19. A controller for controlling a light output of a light  
source, the controller including a non-transitory computer  
readable medium and a processor, the controller including  
computer executable instructions stored in the computer  
readable medium for controlling operation of the controller  
to:

control the light source to produce a first light output with  
a first chromaticity and a first spectral power distribu-  
tion;

receive an input related to an adjustment of a lighting  
effect;

generate a target spectrum based on the input; and

control the light source to produce a second light output  
with the first chromaticity and a second spectral power  
distribution, the second power distribution approximat-  
ing the target spectrum.

20. The controller of claim 19, the controller further  
including computer executable instructions stored in the  
computer readable medium for controlling operation of the  
controller to:

receive, via a selection mechanism of an interface, a value  
for the lighting effect.

\* \* \* \* \*